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REFERENCE

Lane, B. H., 1935, Suggestions to authors of papers submitted for publication by the United States Geological Survey: U. S. Geol. Survey, Washington, D. C. (For sale by Superintendent of Documents, Washington, D. C. 35c.)

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THE EMPLACEMENT OF "GRANITE"[1]

MATT WALTON

ABSTRACT. A general statement of the granite problem develops from the idea that most granite is formed in geosynclinal belts by equilibriopetal processes in which rocks approach compositions and configurations of greater thermodynamic stability following orogenic dislocations in the P-T environment. Alkalis and some other components of granite are less capable than other important rock-forming elements, such as iron, calcium, and magnesium, of forming solid phases in higher temperature and perhaps higher pressure regions, so a potential exists for relative migration of granite-forming elements from such regions. Theoretically, this potential can motivate either processes of diffusion and metasomatism or the formation, migration, and resolidification of a separate fluid phase. The distinction is drawn between demonstrating a potential and showing what process it effectively drives. The problem is to define the limiting conditions for these processes, and establish rigorous criteria for them. In regionally metamorphosed terrains there is strong evidence for granitization, but magmatic emplacement is not excluded. In unmetamorphosed terrains most, if not all, granite must be magmatic. The concept of degree of harmony between the energy level represented by granite and the regional energy level represented by the metamorphic status of the enclosing rocks is set up as a basis for defining certain limiting energy requirements of metasomatic and magmatic processes. The room problem is shown to have both a "positive" and "negative" aspect. Where it can be shown that granite occupies space made by dislocations in the country rocks and that none of the country rocks is missing, it is as fatal to a replacement hypothesis as the demonstration of replacement without dislocation is to a magmatic hypothesis. It is shown that under conditions of moderate to high grade regional metamorphism granite should be mobile relative to common metamorphic rocks and may readily become mobilized and assume intrusive magmatic relations to its surroundings.

INTRODUCTION

This paper started out as a brief commentary on a recent paper in this JOURNAL by R. Perrin (1954) in which he outlined the extreme transformist point of view on the so-called granite problem. Once having seized the dilemma by the horns, as it were, it became difficult to let go without a fairly extensive review of the problem as it appears to me. This essentially independent paper is the result, but it will be apparent from the frequent references to Perrin, which unless otherwise stated will be to the paper cited above, how much his rather extreme point of view has been used as a springboard toward a more eclectic approach.

Perrin opens his paper with an amusing and unfortunately somewhat justifiable remark to the effect that the opinions of petrologists on the problem of the genesis of granite appear, in the present state of our knowledge, to be largely controlled by factors of personal psychology rather than by clearly logical argument. This being even partly true, it would seem desirable to present a concise statement of the problem which will reduce it to its simplest

[1] It is perhaps unnecessary to remark to the sophisticated reader that in discussions of this kind it is tacitly assumed by longstanding custom that the word granite means the whole class of quartz-feldspar rocks of plutonic habit, of which granite is in the strict sense a somewhat subordinate member. With this word to the wise the quotation marks will henceforth be omitted when the term granite is employed.

and most fundamental terms and at the same time avoid the pitfalls of semantically "loaded" expressions. Perrin, drawing heavily on Ramberg, makes some comments on the thermodynamic equilibrium relations of the alkali elements versus iron and magnesium which it seems to me might serve as a basis for the general statement of the granite problem. From such a statement one might hope for a clearer perspective of the conflicting points of view. If the conflict is to some extent psychological, we can hope that a better insight into its precise nature will resolve some of the emotionalism which, it is evident from the heat with which the subject has been debated, now surrounds it. Is this not one of the basic techniques of psychotherapy?

THE GEOCHEMICAL POTENTIAL

It is now generally agreed that most granites arise during or close on the heels of orogenic cycles in geosynclinal belts. Perrin, Ramberg, and many others have pointed out that the accumulation of sediments and volcanics in thick geosynclinal masses and their deformation involve major dislocations in the conditions of pressure, temperature, and stress to which the sediments and volcanics, as well as the orogenically active subjacent basement, had previously made some kind of adjustment. The ensuing petrogenic events, which include metamorphism and the formation of granite, can be regarded as equilibriopetal processes leading to an assemblage and configuration of greater thermodynamic stability.

Like most very broad generalizations, this one has little direct utility, but it does define an attitude or an approach that is worth following up. We must ask now what is the nature of the instability and in what direction does stability lie. Perrin makes reference to Ramberg's (1952a) analysis of the distribution of cations in silicates in which Ramberg shows that there is a tendency for a partitioning of the metallic cations according to their relative electronegativity (Pauling, 1945, p. 58-75). The more electropositive elements, i.e. the alkalis, are relatively more stable in phyllosilicate and tectosilicate structures; the less electropositive elements such as iron and magnesium are more stable in nesosilicate and inosilicate structures.

Perrin does not make it entirely clear why this should lead to long distance diffusions of ions from place to place. It is clear that if the relationship described by Ramberg does exercise an effective influence over the partitioning of cations in silicates then there should be a tendency for, say, magnesium atoms to enter nesosilicates and potassium atoms to enter tectosilicates *in the same place*, that is, when both are entering into crystal structures in the same environment, but this does not fully answer the question of why ions leave home. To complete the answer it is necessary to show that the silicate structures preferred by alkalis are less stable in certain thermodynamic environments than the silicate structures preferred by iron and magnesium and vice versa. I suppose Perrin's implication is that the kinds of silicates preferred by alkalis are less stable in the deeper and hotter regions of the Earth than the kinds of silicates preferred by iron and magnesium, and if alkalis cannot enter phases stable under deep-seated conditions, they will presumably have to move to a less hostile environment, or the environment will have to change before they can come to rest in a stable solid phase. And of course this is a generali-

zation that is acceptable to diffusionists and magmatists alike. After all, it is inherent in Bowen's reaction series.

Perrin also makes a rather ambiguous reference to the idea that the larger and lighter atoms (the alkalis) tend to migrate upward through the oxygen frameworks of the silicate minerals and displace the heavier and smaller ferromagnesian atoms downward under the influence of the Earth's gravitational field. One wonders if this theory is adequate to explain the distribution of such relatively small and heavy ions as Ta, U, Ge, Ga, etc., and even Be and Si. Of course Perrin remarks that Si is freed in the depths by the formation of ferromagnesian orthosilicates, but its large valence, small size, and firm bonds with oxygen make its upward migration by lattice diffusion hard to visualize, and if intergranular diffusion is necessary to account for the migration of Si (to this we can add H_2O), why insist on large scale lattice diffusion for Na and K? Rosenqvist (1952, p. 17-30) has recently made some quantitative estimates of the relative effectiveness of lattice versus intergranular diffusion, which strongly favors the latter, and Verhoogen (1952, p. 651) has shown that lattice diffusion of silica in silicates must be extremely slow. Indeed the measured diffusion rates of iron and magnesium in quartz are extremely slow, and in general diffusion rates through crystal lattices diminish sharply with increasing charge on the diffusing ion. Moreover, if the gravitational potential is all that is required to set this granitizing countercurrent of ions in motion, one wonders how the basaltic crust beneath the more than half the globe that floors the ocean basins can have escaped granitization through geologic time. Still we can admit that the potential is there even if there is some question about how it alone can become effective.

The foregoing considerations suggest a generalized statement of the stability relations of alkalis and ferromagnesian elements in the lithosphere, to wit: *The alkalis are less capable of entering stable solid phases at depth in the Earth's crust than the ferromagnesian elements, and a potential exists for their relative movement upward.* Who can object to this? Experiment, theory, and geological observation from all points of view converge on this conclusion.

It is important to point out at once that the above statement is not an argument for or against granitization, granite magma, or anything else. It merely describes a potential that exists, which if realized under proper conditions can lead to the formation of granite. The statement that such a potential exists says nothing about *how* it is realized, or indeed *if* it is realized, yet much of the argument on the granite problem shows evidence of confusion on this basic semantic precept. I think it is fair to say that the transformists have been more commonly guilty of this non sequitur than the magmatists. Much of Perrin's argument, for example, is directed toward the demonstration of a potential for differential movements of certain elements, as though the existence of the potential were in itself an argument for its realization *by the process of ionic diffusion.*

HOW IS THE POTENTIAL REALIZED?

With the distinction carefully drawn between the existence of a potential and the process or processes by which reduction of the potential is realized,

the "granite problem" may be put in the form of a disarmingly simple question: *How is the potential realized?*

If we put this question in basic English we reduce the granite problem to an almost idiotically simple question: *How do the elements that help to make granite get away from and form separate rocks than the elements that don't help to make granite?* Do the elements segregate as ions diffusing through crystal lattices or along intergranular paths under the gentle urging of gravity and at relatively low levels of thermal excitation? Or are the resistances to diffusion sufficiently great so that large scale movements are at prohibitively slow rates until unstable crystal compositions break down and yield substantial quantities of fluids (ichor, granitizing solution, magma)? Both processes are motivated by the same potentials; the question is which is realized. We seem to find general agreement that granite-forming elements *do* tend to separate and become localized to form granite under certain geologic conditions. We all agree on some general thermodynamic reasons *why* they should tend to separate from the ferromagnesian elements. We are groping for the answer to HOW.

Answers to this question may come from three lines of attack. One is experimental. Here we have a considerable body of information on the stability relations of silicates in dry melts but very inadequate data on systems containing high vapor pressures of water and other volatiles. However, rapid progress is beginning to be made in this direction. We have very little information on subsolidus exsolution and recrystallization, and experimentation with solid and intergranular diffusion is in its infancy. While some of the work that has been done is highly suggestive in one direction or another, *as yet no one can honestly define on the basis of experimentally established fact the geologically realizable limiting conditions for the formation of granite magma or granitizing solutions, nor can anyone predict what the final texture of a granite should look like if it has crystallized from a magma under plutonic conditions.* Experiment does, however, establish that compositions in the granite field have a minimum melting temperature range as compared with other common silicate rock compositions, and this range is well within geologically attainable temperatures, so that the existence of granite liquids as products of either fractional crystallization or partial fusion is certainly feasible. The question is whether the temperature range of granite liquids and mechanically mobile, partly liquid mixtures falls within the range actually attained in the geological situations in which granite forms. Experiment has not yet fully defined these ranges.

On the other hand experimentation with diffusion has been generally discouraging but so limited that one cannot honestly regard it as conclusive. Perrin's brief reference to diffusion of Na ions through quartz in an electrical field is more misleading than instructive. Actually, diffusion of ions under the influence of an electrical potential has no direct application to any real geological situation unless Perrin seriously means to suggest that perfectly staggering electrical potentials exist between neighboring rock masses in the crust. For further experimental work on diffusion rates of alkali ions through quartz at elevated temperatures in an electrical field and a serious appraisal

of the geologic implications of the results the reader is referred to Verhoogen (1952). Solid diffusionists will take small comfort in this work.

The fields of grain-boundary diffusion and diffusion through intergranular fluids or films of various dispersed phases such as water have hardly been explored at all, but a few experiments as well as some by-products of recent experimentation with aqueous silicate systems suggest that this kind of diffusion may be of major geologic importance. Rosenqvist (1952) has shown that known diffusion rates in liquids permit quantitatively significant estimates to be made of the role of intergranular diffusion during metamorphism. The troubles encountered by experimenters in keeping silica from migrating around through the vapor phase in hydrothermal apparatus (Bowen and Tuttle, 1949) and the powerful mobilizing influence of high vapor pressures of water on the exsolution of albite from homogeneous potash-soda feldspar (Bowen and Tuttle, 1950) are intriguing. We can only conclude that actual experimentation to date points toward pure solid diffusion being effective only within dimensions of the order of crystal grains, while other kinds of diffusion may be effective on a much larger scale but have been insufficiently investigated experimentally to quantitatively evaluate their geologic role.

A second line of attack is by theoretical thermodynamics and crystal chemistry. The complexity of silicates and silicate systems and the limited amount of fundamental data restrict the effectiveness of this approach. As is so frequently the case with thermodynamic problems, it is sometimes possible to predict the direction that geologically interesting reactions should proceed under equilibrium conditions, but the calculation of reaction rates and prediction of the paths taken by reactions from reactants to products are generally beyond the reach of theoretical determination. Unfortunately, if we are to answer the question, "how," the paths and the rates are precisely the things we need. We can theorize that a certain ion is more stable here than there, but how it gets from here to there, or if it gets from here to there at all within a reasonable interval of time generally defies theoretical analysis in the present state of our knowledge.

Finally we have the classical geologic approach of deduction from the appearance of things in nature. The elusive thing about the granite problem and plutonic geology in general is that we never can observe actual processes in action. We must guess at processes from the appearance of things long after the processes have ceased to operate. Nevertheless, the human mind being subject, as Perrin has suggested, to illogical enthusiasms, we are apt to speak as though we were observing processes when we are actually looking at products. Shadowy outlines of darker rock within a granite are described by one geologist as inclusions in the process of assimilation and by another as skialiths. The one implies a magmatic process, the other a metasomatic process, neither of which has actually been observed. In fact a great deal of the evidence that has been cited both for and against granitization is essentially textural and structural, and yet we have virtually no *direct* knowledge of how textures are influenced by plutonic processes, or what the mechanical behavior of plutonic magmas and other semi-liquid to liquid or supercritical gaseous bodies would be relative to more or less solid rock. Nor do we have any direct

knowledge of how or if diffusion processes can produce sharp gradients and intense localization of substances that in the same environment are supposed to be diffusing over long distances. A great deal of argument is based on more or less intuitive interpretations of "the looks of things."

THE EXISTENCE OF GRANITIZATION

Nevertheless, the appearance of things is in many cases sufficiently convincing to leave little room for doubt. Thus no one seriously questions that large scale metasomatism can be effective in ore deposits, in contact metamorphic aureoles, and in regionally metamorphosed terrains where granitized rocks display convincing relicts of former sedimentary minerals, textures, and structures. In the nature of the phenomena there can be no direct evidence whether the process is essentially solid diffusion, diffusion through a liquid or gaseous intergranular mesostasis, or transport by fluids streaming through the rock. The energy requirements of diffusion processes are also unknown. However large scale metasomatism must be regarded as a demonstrated fact, and it would be foolhardy in the present state of our knowledge to place close or arbitrary strictures on the part that it may play in the emplacement of granite.

THE EXISTENCE OF GRANITE MAGMA

I think there is also a tendency today to under-rate the direct evidence for the existence of granite magma and its connection with granite plutonism. It is probably a little old-fashioned to point out that granite magma has been seen in the form of rhyolite flows pouring in copious quantities from holes in the ground. In this respect granite magma has a distinct advantage over currents of diffusing ions. It is fashionable, on the other hand, to deprecate the geologic role of rhyolite with the oft-repeated assertion that rhyolitic volcanism is trivial in quantity compared to basaltic volcanism. This statement is misleading and to a substantial degree downright incorrect. Basaltic volcanism takes place dominantly in stable ocean basins or continental cratons or in geosynclines during the period of sedimentation. Furthermore, basaltic volcanics tend toward widespread, compact lava flows with subordinate pyroclastics. Both in physical character and geologic environment basaltic volcanics are admirably suited for preservation in the geologic record. On the other hand, rhyolitic volcanism takes place in mountain belts during active mountain-building and runs to pyroclastics and rugged volcanic piles of restricted extent. Rhyolite volcanics are perhaps more generally open to attack and destruction by the processes of denudation than any other kind of surficial deposit. Nevertheless, as detailed knowledge of the cordilleran belts grows, we are constantly revising upward our estimates of the quantity of rhyolitic volcanics, which are so commonly disguised as ash beds, welded tuffs, etc., mixed with sediments, while careful analysis of orogenic sediments in basins of deposition far removed from the orogenic belts increasingly reveals large contributions in the form of clay derived from primary acid pyroclastic material. When C. S. Ross' (1951) paper is ultimately published *in extenso*, an impressive amount of supporting data will be available in the literature. Moreover, as the so-called granite bathyliths are studied in detail it becomes obvious that we have tended grossly to overplay the role of granite (Larsen,

1948). Intermediate types generally greatly exceed in amount the true granites in the larger bathyliths, and so we must take into account the corresponding intermediate volcanics in addition to the rhyolitic end member.

While basaltic rocks are ubiquitous, granite itself is limited in its geologic occurrence, for it is largely confined in place to the orogenic belts and in time to the orogenic episode if, as has been frequently suggested (Holmes, 1946), the broad displays of granitic rocks in the Precambrian shields represent the welding together of successive orogenic belts. In other words, granite is itself confined to the same geologic environment in which we find rhyolite volcanism. Nor should we be disappointed if we do not commonly find granite bathyliths in close association with rhyolite volcanics, for it stands to reason that rhyolite volcanics that were synchronous with the emplacement of a bathylith are destroyed by erosion and deposited as sediments elsewhere long before the bathylith is laid bare. When due consideration is given to the above facts it becomes evident that nature has suppressed and disguised a great deal of direct evidence for granitic magma in the form of acid volcanism. It must be more than coincidental that acid volcanism proves to have the same coextensive relations in time and place to orogeny as does the emplacement of the acid plutonic rocks.

INTRUSIVE MECHANISMS AND THE ROOM PROBLEM

Another straw man that is regularly erected and then demolished with a few words by those bent on banishing magmatic granite from the terrestial scene is the so-called "room problem." Now the room problem is indeed a very great problem but not so clearly incapable of a mechanical solution as to warrant the cavalier treatment it has received at the hands of granitizers. Stoping mechanisms have received some attention, and while the evidence for piecemeal stoping is not impressive, ring dike, cauldron subsidence, and other permissive mechanisms are supported by substantial field data. However, I am inclined to think that these are not really important mechanisms for the large intrusions. Geologists familiar with salt domes see on a scale comparable to granite stocks a clear demonstration of how lighter and more mobile material impelled by nothing more than its gravitational potential can punch its way up through tens of thousands of feet of overlying strata (Nettleton, 1934, 1943; Balk, 1949, 1953). The structural dislocations produced by salt domes in the surrounding rocks are scarcely noticeable beyond a few hundred meters and would escape attention if the rocks involved were not well stratified, otherwise undeformed, and capable of close stratigraphic correlation. Grout (1945) has shown experimentally the relative movements of magma and country rock involved in this type of intrusion, and Noble (1952) with a field example of remarkable clarity has shown how the structural dislocations produced by rhyolite magma rising through schistose deformed rocks are virtually impossible to distinguish from the effects of regional deformation but can be demonstrated with precision in well-stratified rocks that overlie the schists unconformably. Here is a mechanism of intrusion that works on a scale from the laboratory model to salt domes of bathylithic proportions (over 40 square miles outcrop area) (Harrison, 1930) and duplicates an entire complex of features seen in granite plutons. It even produces the geochemical counter-

current demanded by the broad thermodynamic picture, for the alkalis (in the form of salt) rise, displace the heavier rock materials by doming, stretching, and shouldering aside, and the heavier materials subside into the position vacated by the salt. Moreover, temperature at the depths of the salt formations from which the salt intrusions arise is on the order of 300°C. (Balk, 1953). This is supposed to be in the range in which active diffusion of alkalis takes place, but here the "geochemical equilibrium" is restored by an entirely mechanical process. Geologists must keep in mind the simple aphorism that there is more than one way to skin a cat.

In fact, the "room problem" may be turned against the transformists in a rather neat way where good exposures, simple regional structure, and close stratigraphic control permit accurate account to be kept of the country rocks in which an intrusion has been emplaced. Hunt (1954) has shown that the intrusion of the diorite plutons that form the celebrated Henry Mountain laccoliths involved a lifting and shouldering aside of the Mesozoic strata, and the displaced strata can be accounted for practically bed by bed and volume for volume. In other words nothing is missing except what later erosion has removed. Now if a rock mass formed by replacement, it presumably replaced something, but if it is shown that nothing is replaced, merely displaced, the replacement hypothesis meets what one might call a "negative room" problem that really is fatal.

Recent work of my own (unpublished) in the eastern part of the Adirondack mountains of New York has demonstrated that where a detailed knowledge of the sequence of rock units and the structure can be worked out it can be shown that certain granites occupy structural situations where certain members of the Grenville metasedimentary sequence are missing. Other granites, notably the rocks of the so-called pyroxene-quartz syenite series (Buddington, 1939), occupy structures in which strong dislocations in the Grenville metasediments can be demonstrated and in which all known members of the Grenville metasedimentary sequence are present, wrapping around the granitic masses. If a granitization origin is claimed for these latter granites it is necessary to postulate, entirely *ad hoc*, that some metasedimentary rock unit has been granitized that has never been recognized and for which there is no field evidence. These relationships suggest that the room problem can have both positive and negative solutions, as it were, and may not be appealed to unless one or the other has been demonstrated quantitatively in the field.

It seems impossible to escape the conclusion that nature has provided abundant direct evidence of the existence of granite magma in the geologic environment in which granite plutons form, and has also provided direct evidence on a substantial scale that adequate intrusive mechanisms exist. Therefore when a metasomatic explanation meets great difficulties it seems reasonable to accept as a possibility the hypothesis of magmatic emplacement.

THE SIGNIFICANCE OF "DISHARMONIOUS" GRANITES

Now it seems to me that there are certain geologic environments in which granitic bodies up to major bathylithic size are occasionally emplaced that present insuperable difficulties to granitization hypotheses. These are the terrains of entirely unmetamorphosed sediments invaded by granite masses

that are surrounded by well-defined, high temperature contact metamorphic aureoles. Here it is plain that the level of thermal energy represented by the granite is completely out of harmony (Walton, 1953b) with the regional energy level represented by the unaltered sediments. The term "disharmonious" refers to a discontinuity in temperature between the granite and its surroundings as compared with the more common term "discordant" which refers to a physical or structural discontinuity. The contact metamorphic aureole in which minerals such as clays, stable at surface temperatures, are recrystallized into minerals stable at higher temperature proves that the disharmonious granite mass represents a highly localized source of heat in a low temperature environment. The Boulder bathylith of Montana (Knopf, 1950, 1953) is an example of a very large bathylith of granitic rocks that is out of harmony with the regional metamorphic level. It is emplaced in rocks that include shales, argillites, and fossiliferous dolomite and limestone. These rocks are strongly metamorphosed up to the rank of sillimanite-cordierite-microperthite hornfels in a well-defined contact aureole.

If granitization is to be regarded as a consequence of metamorphic processes, it implies that a substantial level of thermal energy must be reached in order to activate a diffusion process of sufficient intensity and velocity to convert bathylithic volumes of sediment into granite. Perrin himself along with most other advocates of granitization speaks of a general rise in temperature being required to allow diffusion to begin in geosynclinal accumulations of sediments. Where then is the highly localized source of heat necessary to activate granitization in the unmetamorphosed terrains where sharply transgressive granites have been emplaced at shallow depths? Vague references have been made to heating during granitization by exothermic reactions (Ramberg, 1952b, p. 274). So far not a single specific reaction or bit of quantitative thermodynamic data has been adduced to support this bald assertion. On the other hand, it is well known to most geologists that granites break down in the low temperature surface environment to yield sediments; and granitic mineral assemblages may be made to crystallize experimentally at high temperatures above the stability ranges of many of their sedimentary decay products. The direction taken by these reactions indicates that the conversion of sedimentary mineral assemblages into granite is an endothermic process. As advocates of granitization themselves have long argued in connection with the relations of granite to metamorphism, the conversion of sediments into granite represents a reorganization of phases stable at low temperatures into a new phase assemblage stable at higher temperature, which implies in general an absorption of heat. If the general level of energy sufficient to activate granitization were as low as would be indicated by some of the granites emplaced in unmetamorphosed terrains, the wonder is that bricks and mortar can long preserve their identity in any chimney pot. Certainly adequate and measurable diffusion processes would be easily realizable in the laboratory if such low potentials were involved.

In making sweeping claims for the metasomatic emplacement of practically all substantial masses of granite, I suspect that the metasomatists have extended their hypothesis from the metamorphic environment, where most

granites are found and where there is convincing evidence that granitization is an important process, to an environment where it won't work. In so over-extending their hypothesis they have taken the easy way out of a "room problem" which they have made no serious effort to solve, and have rather surreptitiously substituted a "heat problem" which they have also made no serious effort to solve, at least where highly localized, high temperature heat sources in a low temperature domain are demanded by the geologic facts. The only adequate means as yet known of introducing a large, localized source of heat at a high temperature into a relatively shallow, unmetamorphosed sedimentary environment is by introducing an adequate amount of hot material with a high heat capacity—or, to put it bluntly, by an intrusion of hot, mobile rock material—or even more bluntly, by hot magma.

I would suggest that strong "disharmony" with the regional level of metamorphic energy as evidenced by high temperature contact metamorphic effects on unmetamorphosed country rocks is proof of magmatic emplacement of a granite. To granites of this kind we may turn to test the validity of criteria for and against magmatic emplacement. I will venture to say that in some granite masses of this type we will find screens, septa, beds, bands, and relicts of country rock parallel with the contacts. We will find the strikes of enclosing rocks in many instances swinging into parallelism with the granite contact, and we will find textural and mineralogical banding and lineation parallel with the contacts. After all, all these features are exhibited by salt plug intrusions. Granitizers must face the fact that there are more ways of producing structural parallelisms in rock units than simply by processes of sedimentation. Mere parallelism of structural elements and lithologic units in a rock mass does not demonstrate that it was once a stratified sedimentary deposit.

The crystalloblastic textural features exhibited by disharmonious granites must be explained by the so-called endomagmatic exsolutions and recrystallizations (Tuttle, 1952), and the old-fashioned concepts of assimilation, contact metasomatism, and diffusion motivated by the heat and fluids emanating from a cooling magma must suffice to explain the textural and compositional changes and the "geochemical culminations and depressions" that are found in the contact aureoles.

Transformists are so ready to accept the idea of long-range diffusions under low potentials that it is difficult to understand why they should reject the idea of subsolidus endomagmatic reorganization of a granite fabric by diffusions on the scale of single crystals during the prolonged cooling of a rock that is shown by its contact effects to have been at high temperature. I would suggest that the "disharmonious" granites prove the possibility of endomagmatic origin of the granitoid fabric rather than that the granitoid fabric proves the metasomatic origin of the "disharmonious" granites. Similarly, metasomatic replacement features and evidences of diffusion seen at the contacts of such granites are no proof that the entire granite formed metasomatically. They merely show that a hot granite in the process of crystallizing and exsolving volatiles can, as one would infer, engage in a lively chemical exchange with its contact rocks. Where strong disharmony exists between granite and country rock in terms of the energy levels evidenced by contact

metamorphic effects, the magmatic origin of the granite must be accepted, and to granites of this kind we may safely turn for an understanding of the fabrics, structures, and contact relations that may develop during magmatic and endomagmatic processes.

GRANITES IN METAMORPHIC TERRAINS

However strong the foregoing argument may be for the existence of some magmatic granites, it does not follow that by analogy the argument may be extended to cover all, or even most, granites. For most granites are emplaced in terrains of moderate to strong regional metamorphism, and here the criterion of "harmony" is indeterminate (not negative—just indeterminate). I reported recently (Walton, 1953b) that, near the middle of the amphibolite facies level of metamorphism, eastern Adirondack granites do not exhibit contact metamorphic effects that betoken an elevation in metamorphic rank or endothermic recrystallization of the adjacent country rock. Chemical, mineralogical, and textural effects may be noted but they involve no definite change in metamorphic rank. And in fact, where granites are emplaced in terrains of metamorphic rank corresponding to the higher amphibolite facies or the pyroxene granulite facies, distinct retrograde effects such as scapolitization, sericitization, uralitization, saussuritization, and chloritization may be noted in the surrounding rocks probably induced by a higher vapor pressure of water in the vicinity of the granite, unless the granite tends toward charnockitic affinities. On the other hand, compelling evidence for granitization may be seen in metamorphic terrains in the form of pseudomorphs and relicts of sedimentary minerals, textures, and structures, and it appears to me to be just as extreme to claim a magmatic origin for every thin streak and isolated mass of granitic material in a migmatite as to deny the magmatic origin of what I have here called the obviously "disharmonious" granites.

There does not appear in the present state of our knowledge to be any objective limitation that can be placed on the extent to which granitizing processes may be effective where the mineral assemblages represented by the surrounding metamorphic rocks appear to represent an energy level equivalent to or higher than granite. Here we must consider the possibilities of two processes which may operate together or separately: one, that the energy level of the environment is sufficient to permit the granitizing elements to break their bonds, diffuse, and segregate into granite bodies by one mechanism or another; the other, that in the presence of intergranular water the components of granite begin to pass into solution and form ichors and magmas.

As far as present knowledge is concerned it seems obvious to me that both granitization and granite magma can be shown in certain cases to have operated on a sufficiently large scale to be regarded as major factors in the emplacement of granite, but a broad shadow zone of uncertainty exists between the definable extremes, probably encompassing a major part of the granites of the world, in which we are unable to define the contributions of the two processes with any degree of certainty.

THE SOURCE PROBLEM

Up to this point I have mainly dealt with the more immediate aspect of the granite problem, that is, the processes by which granite is emplaced in

the environments in which we actually see it. We might call this the emplacement problem, and it is the emplacement problem that is the real crux of the controversy between advocates of granitization and magmatic hypotheses. The other aspect of the granite problem might be termed the source problem, and it has to do with the ultimate source of granitic materials. Here there are a number of conflicting views but they do not seem to be so firmly held or bitterly argued, probably because here at least everyone is willing to admit that the various solutions of the problem are based on very inadequate objective information. Broadly the hypotheses that have been argued may be divided into two major categories. One group of hypotheses involves plutonic processes alone. Briefly enumerated they include: primitive acid magma, differentiation of primitive basic magma, remobilization of a primitive granitic crust derived during early consolidation of the Earth, juvenile ichors or granitizing solutions, and migrations of juvenile materials by various diffusion processes. The other group of hypotheses involves a differentiation of crustal materials in which surficial weathering and sedimentation plays an essential part. Briefly these ideas center around accretionary hypotheses for the origin of the sialic continental masses. Anatexis or differential migration processes create granite out of sedimentary materials which have attained compositions favorable for these processes through geochemical differentiations and segregations that take place during repeated weathering and sedimentation of a primitive basaltic crust. Of course there are all shades of blending of the two sets of ideas.

In the course of arguing the emplacement problem a rather entertaining dichotomy develops between granitizers and magmatists on the source problem. Where field and petrographic evidence for the metasomatic emplacement of a body of granite is so conclusive that it cannot be denied, magmatists find the source of the granitizing material and the granitizing energy in a differentiating body of magma. If a suitable body of rock to represent the presumed body of magma is not present in the environs, it can always be assumed to be deeper down.

On the other hand, where the evidence for mechanical mobility and intrusive emplacement of a granite mass is so overwhelming that it cannot be disputed (for some granitizers this practically restricts the argument to active rhyolitic volcanoes), a local, and in the larger picture quite trivial, amount of granite magma will be admitted by granitizers, but this is merely a product of local mobilization or rheomorphism of already granitized rock.

For example, Perrin has advanced the curious idea that diffusions tend to produce an increase in volume at great depth and will build up pressure. "Plastic deformations being impossible," the pressure will be relieved by shearing which will result in fissurization, and thus the high pressure region will become the locus of regions of abrupt decompression. Decompression will be accompanied by partial melting, and a local pocket of magma will be produced whose composition depends on the composition the rock has attained in the diffusion process. The mechanics of the process are so sketchily outlined that I confess I find it beyond my comprehension. So sweeping an idea really demands a detailed presentation supported at least by some evidence that it

rests on reasonable assumptions. The assertion that at depth in geosynclines plastic deformations become impossible owing to the pressure seems to me to be particularly bald and unconvincing. It has always been my impression that the further we go into deeply eroded regions of high grade metamorphism, the more striking becomes the evidence of extreme plastic deformation.

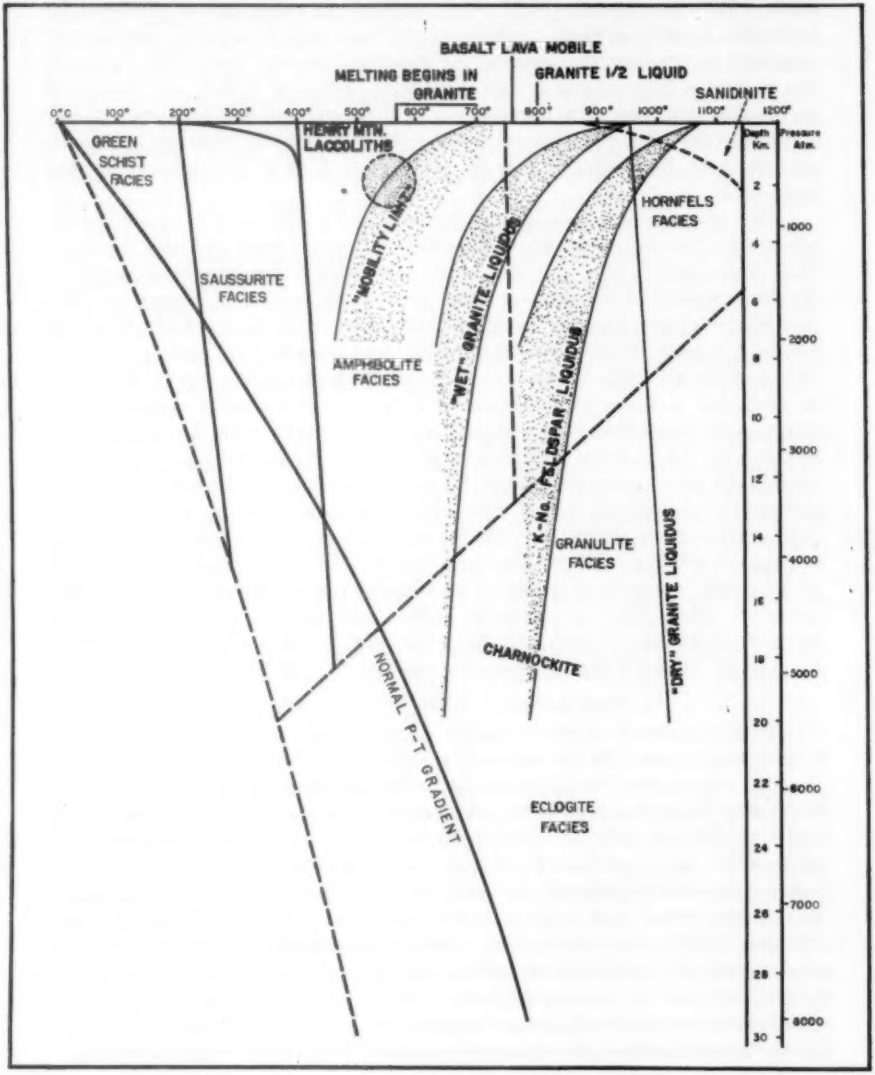
Other strong advocates of granitization have seemed to regard mobile granitic material as a product of relatively shallow, localized processes (Reynolds, 1951; Goodspeed, 1952). Abnormally high temperatures produced by somewhat vaguely defined exothermic processes and fluxing by volatiles are supposed to produce rheomorphic or mobilized granitic materials. Reynolds has argued at Slieve Gullion that rhyolite is produced in this way, emplaced as rhyolite tuff, and then regranitized to form granophyre. In some curious way these rhyolitic materials escape the strictures of the room problem that, according to Reynolds, render the emplacement of a granophyric magma impossible.

The rheomorphic concept has been used by advocates of granitization where they have been unable to escape the evidence of fluid intrusive relations. They have used it in a way that seems to involve a sort of tacit assumption that the velocity of diffusion or other granitizing process is always so great that before a temperature level and volatile content can be reached which will permit a granitic liquid to form the rock must already have been granitized. This is different from the concept of anatexis which implies that an accession of heat and volatiles to ungranitized rocks of heterogenous character can result in the breakdown and reorganization of the rocks, with the passage into solution of the granitic components to form a liquid fraction of granitic magma. In view of our very limited direct knowledge of the rates of diffusion processes, it is difficult to see what objective basis exists for assuming that granitization must always precede the development of a granitic magma by anatexis through partial solution and fusion, and for restricting the mobile or magmatic phase to a minor or subsequent role. If the fusion of granitic materials takes place in relatively shallow volcanic environments such as Slieve Gullion, as advocated by Reynolds, one wonders about the condition of granitic material deeper down in regions of high grade metamorphism.

THE RELATIVE MOBILITY OF GRANITE

In fact, rather than argue against rheomorphism, I am inclined to assign to it a major role. Let us reflect a moment upon the condition of rocks of granitic composition in a plutonic environment when the pyroxene granulite level of regional metamorphism is attained. Can granite be relatively rigid and immobile in such an environment during strong deformation? In the Adirondack region of New York there is abundant evidence that rocks of the pyroxene-garnet amphibolite and even pyroxene granulite facies have undergone extreme isoclinal folding and complete paratectonic recrystallization (Walton, 1953a). Isoclinal folding involves considerable flowage in these high grade gneisses, and isoclinal folding and flowage can be demonstrated to have taken place in massive gabbros, which in the process are converted by paratectonic recrystallization into amphibolite and granulite with such powerful lineation that they are commonly referred to as mafic "pencil gneisses."

What about granite in the same environment? The field relations very strikingly show granite masses of all sizes occupying dilitant structural positions (Mead, 1925), such as the noses of tight folds where they form the so-called phacoliths for which Adirondacks are well known. In places the granite occupies diapir-like structures in the noses of folds closely analogous to the diapirs formed by the break-through of incompetent sedimentary rocks when involved in tight folding with more competent strata. We do not find it neces-



sary to set up a "shalification" hypothesis to explain the intrusive relations of shale in a diapir structure owing to an "insoluble room problem," nor do we entertain a theory of "marblization" to explain the remarkable intrusive relations of the crystalline limestone members of the Grenville series to the less mobile paragneisses. Why pick on granite in the same structural situations when there are abundant reasons for thinking it should be mechanically highly mobile or even fluid where high grade paragneisses are undergoing strong plastic deformation?

Rosenqvist (1952) has recently published an interesting synthesis of experimental, petrographic, and theoretical data on the P-T fields of the principal metamorphic facies. Rosenqvist's diagram summarizing his results is reproduced here as figure 1. On it is superimposed some of the available P-T data on lava and magma temperatures and temperatures in silicate melts under varying pressures of water vapor. It is quite clear that unless Rosenqvist's diagram, which is not markedly different from the ideas of other investigators, is grossly in error, a liquid silicate phase must begin forming in granitic rock materials wherever any water is available at pressures and temperatures quite commonly attained during regional metamorphism. Anyone who has ever mixed up a batch of concrete will know how little liquid is necessary to render a crystalline aggregate mobile. Granite in an environment where the higher grade metamorphic rocks are undergoing plastic deformation must be relatively highly mobile, and also relatively less dense than the surrounding more basic metamorphic rocks. Consequently, it must have a strong tendency to rise

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Fig. 1. Data on magmatic temperatures and an estimate of the range of temperature and pressure within which granite may be mobile, compared with the P-T fields of the metamorphic facies after Rosenqvist (1952).

Two experimentally determined pairs of "liquidus" curves are shown: one pair for the lowest melting-temperature compositions of the K-Na feldspars (Bowen and Tuttle, 1950), and one pair for the melting of granite (Goranson, 1931, 1932, 1938). The upper curve of each pair is drawn on the assumption that the vapor pressure of water in the system equals the static rock pressure, the lower that the vapor pressure of water equals the hydrostatic pressure of a column of water extending to the surface.

A hypothetical curve called the "mobility limit" has been sketched to reflect the fact that the lavas and intrusive magmas are mobile when they are far from completely liquid. The starting point of this curve at essentially zero partial pressure of water vapor is a guess based on the experimentally determined temperature at which a natural granite became half liquid (Goranson, 1932), the range within which the first signs of melting were observable in natural granite (Grieg, Shepherd, and Merwin, 1931), and the minimum temperature for which I could find a record of natural lava (in this case Hawaiian basalt) capable of flow (Macdonald and Finch, 1949). Another guide to the locus of this curve is given by the estimated ranges of temperature and depth within which the Henry Mountain laccoliths were intruded (Hunt, 1954). The form of the "mobility limit" curve is taken from the experimental "liquidus" curves. The field of charnockitic granites is suggested, within the granulite facies and between the "wet" and "dry" granite liquidus curves.

The passage of magma into rock is certainly far from a simple reversible process, but it appears likely that once rock materials become mobile they continue to behave like magmas far below their liquidus temperatures and that granites may become mobile and behave intrusively at fairly moderate levels of regional metamorphism.

While this paper was in press new data on the melting of granite became available (Tuttle and Bowen, 1953), showing that the beginning of melting falls within the stippled area shown here for the "wet" granite liquidus. They state that the melting observed at lower temperatures is a metastable phenomenon, but this does not necessarily invalidate the fact that it does take place. Also note that the pressure coordinates on figure 1 refer to the rock load at the corresponding depth and not water vapor pressure.

en masse and invade the rocks above in a manner quite analogous to the rising salt dome, modified by the structural inhomogenieties of deformed and metamorphosed rocks. Tectonic pressures will also cause granite to move differentially in the direction of easiest relief, which is presumably generally upward in deep-seated environments. Adequate mechanical theory and dimensionally accurate experiment confirm this conclusion (Nettleton, 1934, 1943; Grout, 1945).

CONCLUSION

It has been argued in the foregoing pages that emplacement of granite by metasomatic granitization as well as by magmatic intrusion can be demonstrated convincingly to have worked on sufficiently large scales to both be potentially major processes in the emplacement of granite. As Read (1947) has repeatedly said, there are "granites and granites." This is not mere hyperbole, nor is it fence straddling. It must be accepted as an established basis for further progress toward a thorough insight into the granite problem. It is also quite clear that in the present state of knowledge the limiting conditions and the relative roles of neither magmatic emplacement nor metasomatism have been defined by experiment, by adequate and detailed thermodynamic theory based on valid fundamental data, or by the establishment of unequivocal, decisive field and petrographic criteria. Probably most of the granites known to us fall in the broad shadow zone between the few extreme examples that we can with some confidence ascribe to one major process or the other. Real progress will be made when we recognize the inadequacy of our knowledge and the limitations and ambiguities of our methods. Experimental work, thermodynamic theory, and field and petrographic study all present unlimited opportunities for extending our insight into the granite-forming processes.

From the standpoint of one who is primarily a field geologist I have already suggested in these comments two approaches that should give further definition to the roles played by magmas and metasomatism. Let us systematically consider granites in terms of their relationships to regional levels of metamorphism. Let us try to find what are the systematic differences in textures, fabrics, internal and external structures, parageneses, and geochemistry between the strongly discordant and disharmonious granites and the granites of the metamorphic terrains. Strongly disharmonious granites are admittedly uncommon and perhaps peculiar, but out of their study we may hope to define those features that can develop entirely out of the magmatic, endomagmatic, and contact metasomatic processes, as contrasted with those that require some appreciable level of regional metamorphic energy. We then may really know what we are talking about when we use textural criteria to establish a mode of origin. An excellent start on a facet of this problem has already been made by Tuttle (Tuttle 1952; Tuttle and Keith, 1953), backed up by brilliant experimental work. We may also hope to find limiting levels of regional metamorphism at which granites begin to show evidence of harmony or disharmony with their surroundings, and out of this may come definition in terms of metamorphic facies of the limiting energy requirements for effective diffusion processes. There must be limits, or large scale diffusion would have long since been easily realized in the laboratory.

Another approach by which the field geologist may be able to make a decisive contribution to the granite problem is by a more intensive, quantitative approach to the room problem. The distinction must be made between suggestive evidence in the form of contact effects, structure, textures, etc., that to one mind is consistent with magmatic intrusion, and to another with metasomatic replacement, and quantitative proof to at least reasonable orders of magnitude that a granite did or did not produce commensurate dislocations in the pre-existing rocks during its emplacement or does or does not occupy a place where some known unit is missing. Too much work on granite has ended at the contacts. Petrologists who are interested in the granite problem will have to engage in intensive structural and stratigraphic work in the regions surrounding granite bodies before making assertions regarding the room problem.

It is true that many granites are inadequately exposed or are emplaced in terrains that are structurally so complex and so lacking in stratigraphic controls that quantitative answers can probably never be found for the room problem. However, it is not too much to hope that here and there granites will be found where an adequate, quantitative, objective appraisal of the room problem can be made. I suspect that as this kind of knowledge builds up we will find that certain kinds of granite are accompanied by dilatation and structural displacements commensurate with their volume, while others occupy places where something is missing, and that there are all shades of gradation between these extremes. By studying the extremes we may then be able to get an independent check on the validity of the various petrographic, chemical, and structural criteria that have been applied with such controversial results to the granite problem.

Above all let us not feel that every granite that we study demands a pronouncement from us on its mode of origin. Probably most granites are truly indeterminate as matters now stand. From the psychological standpoint we must learn to live with a mild condition of schizophrenia lest a premature attempt at resolution lead only to delusions of grandeur. The wonder is not that there is a difference of opinion at the present time among petrologists on the origin of granite, but that as scientists we can hold passionately to any strong and mutually exclusive opinions at all.

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THE CLAY MINERALS AND THE IRON OXIDE MINERALS OF THE TRIASSIC "RED BEDS" OF THE DURHAM BASIN, NORTH CAROLINA

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ABSTRACT. X-ray diffraction analyses of the clay fractions of 50 Triassic arkosic "red beds" and 4 "non-red beds" of the Durham Basin reveal that (1) illite and montmorillonoids are the most abundant clay minerals, kaolin and vermiculite being of secondary importance, and (2) hematite is the only crystalline iron oxide present although the samples vary in "red" color. The clay minerals and iron oxides probably were derived by the deep erosion of red lateritic soils, the illite and montmorillonoids having come from the partially weathered bedrock (C-horizon) and the kaolin having come from the upper, more thoroughly leached parts of the residual mantle (A- and B-horizons). The variations in the color of the "red beds" are probably the results of variations in the size of the hematite grains.

INTRODUCTION

The clay fraction of 50 more or less random "red bed" and 4 "non-red bed" samples from the Triassic sediments of the Durham Basin of North Carolina were analyzed by X-ray diffraction techniques to determine the clay minerals and the iron oxide minerals that characterize these sediments. The writers had two main questions they wished answered: (1) Are the clay fractions of arkosic sediments composed mainly of kaolinite as implied by Krynine (1948, p. 137, 148-149) and Krumbein and Sloss (1951, p. 131, 136)? (2) Are the variations in iron oxide colors caused by the presence of different iron oxide minerals? For the specific case of the arkosic sediments of the Triassic sediments of the Durham Basin, the answer to both of these questions is "No." In addition to answering these questions the writers have been able to speculate on the origin of the clay minerals in these sediments.

GENERAL GEOLOGY

The Durham-Deep River Triassic Basin extends in a north-south direction almost all the way across North Carolina. The northern part of the basin above Sanford has been given the name Durham Basin (Prouty, 1931) (fig. 1). The Durham Basin averages 10 miles in width and is nearly 70 miles long, extending from just south of Oxford southwestward to Sanford.

Sedimentation occurred in a sinking fault trough along the eastern edge of the Piedmont Plateau. Surrounding the Triassic sediments are Precambrian (?) gneisses and schists, Precambrian(?) or Ordovician(?) volcanic rocks and slates, and Carboniferous(?) granites. These were the source rocks of the Triassic sediments.

The Triassic rocks of the Durham Basin have not been studied in any great detail. Reconnaissance studies have been made by Shearer (1927), Prouty (1931), and Murray (1937). These sediments are mainly gray arkoses, feldspathic sandstones, shales, and mudstones lensing with "red" arkoses, feldspathic sandstones, quartz-mica sandstones, shales, and mudstones. The color of these "red" sediments is highly variable, as shown in table 1. Carbonaceous shales and sandstones occur locally. Along the fault marking the eastern border of the basin are extensive pebble, cobble, and boulder con-

glomerates. Numerous dikes and sills of basalt, diabase, and gabbro have intruded the sediments. In general the beds have a monoclinal dip to the southeast of from 5° to 20°.

FIELD AND LABORATORY PROCEDURES

Samples of sandstones, siltstones, and clayrocks were collected throughout the Durham Basin to obtain a suite of samples with maximum range in "red bed" colors. A few non-red samples were collected in order to compare their clay mineral contents with those of the "red beds." The locations of these samples are shown on figure 1.

After dispersal in 0.01 N sodium hexametaphosphate (Calgon), the fine clay with a diameter of less than 1 micron was separated by centrifuging and dried at 80°C. The fine clay was used because it usually contains only a very small amount of quartz and because it usually contains a concentration of the iron oxide particles. Untreated and glycerol-solvated samples of each clay were X-rayed. Samples that gave patterns with 14 A lines or 10-14 A bands were heated for ½ hour at 550°C. and re-X-rayed. A Hayes X-ray diffraction unit with powder cameras 114.6 mm in diameter was used. The samples were placed in thin-walled, cellulose acetate tubes and were photographed with either filtered iron or copper radiation. For the determination of the iron oxides, iron radiation was used.

RESULTS

Color and iron oxide mineralogy.—The hand specimens differ in color with shades of brown, red, orange, and pink being represented in the suite of samples (table 1). Over half of the "red" samples are some shade of brown, and most of these brown samples are either pale reddish brown (10R5/4) or moderate reddish brown (10R4/6). Color designations are according to the National Research Council "Rock-color Chart" (Goddard, et al., 1948).

Hematite was the only crystalline iron oxide mineral identifiable from the X-ray patterns. If other iron oxides are present, they either are present in quantities too small or are too poorly crystalline to register diffraction lines. Most of the hematite occurs as fine particles evenly disseminated in the clay, although many of the sand grains have an irregular coating of fine hematite particles.

TABLE 1

Sample Number	Color of Hand Specimen*	Clay Minerals**	
		Abundant or Common	Rare or Trace
1	mod. red. brn. 10R4/6	M, I	
2	pale red. brn. 10R5/4	I, M	K(?)
3	pale red. brn. 10R5/4	M	I
4	pale red 10R6/2	M, I	K
5	pale red. brn. 10R5/4	M, I	Kh
6	pale red 5R6/2	M, I	Kh
7	mod. or. pk. 10R7/4	I, Kh	
8	mod. red. brn. 10R4/6	I	V(?), Kh
9	pale brn. 5YR5/2	V	I
10	pale red 5R6/2	M, K	
11	pale red. brn. 10R5/4	M, Kh	
12	lt. brn. 5YR5/6	I, M	

13	mod. red. brn. 10R5/6	I, K, M	
14	pale red. brn. 10R5/4	I, M	Kh
15	mod. red. brn. 10R4/6	I, M	
16	mod. red. brn. 10R4/6	I	M(?)
17	pale red 5R6/2	I, M	K
18	lt. brn. 5YR6/4	I, M	Kh
19	pale red. brn. 10R5/4	M	I, Kh
20	pale brn. 5YR5/2	I	Kh, M
21	pale red. brn. 10R5/4	I	M
22	mod. red. brn. 10R4/6	M	
23	pale red 10R6/2	M	Kh, I
24	pale red 10R6/2	M, I	
25	mod. red. or. 10R6/6	M	I, Kh
26	pale brn. 5YR5/2	M	I, Kh
27	pale red. brn. 10R5/4	I, M	
28	pale red. brn. 10R5/4	I, M	
29	pale red. brn. 10R5/4	I	M, K(?)
30	pale red. brn. 10R5/4	I	K, V
31	mod. red. or. 10R6/6	I, M	
32	pale red 10R6/2	I	K, M(?)
33	mod. red. brn. 10R4/6	I, M	
34	mod. red. or. 10R6/6	I, V	K(?), M(?)
35	pale red. brn. 10R5/4	I, M	Kh
36	mod. red. or. 10R6/6	I, M	K
37	pale red. brn. 10R5/4	I, M	Kh
38	pale brn. 5YR5/2	I, M	Kh
39	pale brn. 5YR5/2	I, M	
40	pale red. brn. 10R5/4	I, M	Kh
41	gry. red 10R4/2	K, I	V(?)
42	mod. red. brn. 10R4/6	M, I	
43	pale red 10R6/2	I	M, Kh
44	pale red 5R6/2	K, I	V
45	pale red 10R6/2	M	I
46	pale red. brn. 10R5/4	I, K	
47	pale red. brn. 10R5/4	M	I
48	pale red. brn. 10R5/4	K	I(?)
49	mod. red. or. 10R6/6	Kh	
50	gry. or. pk. 10R8/2	M	
53	ylw. gry. 5Y8/1	M	
54	ylw. gry. 5Y8/1	M	
55	ylw. gry. 5Y8/1	M	K
56	lt. brn. gry. 5YR5/1	I, M	

* Color names from National Research Council Color Chart.
** K-kaolinite, Kh-halloysite(?), I-illite, V-vermiculite, M-montmorillonoids.

Clay mineralogy.—Illite, montmorillonoids, kaolin, and vermiculite were identified in the samples (tables 1 and 2).

TABLE 2

Frequency of Abundance of Clay Minerals

	Percentage of Samples in which the Mineral is the Most Abundant	Common or Abundant	Rare	Absent
Montmorillonoids	37	70	15	15
Illite	53	68	15	17
Kaolin	7	17	44	39
Vermiculite	2	4	7	89

Illite and montmorillonoids predominate in nearly all of the samples (table 2). About half of the kaolin is definitely kaolinite. Much of the re-

maining half could possibly be halloysite as this material gives a diffraction pattern with a broad 7 A line or a 7-10 A band. The vermiculite has a 14 A basal spacing that does not shift with glycerol solvation but does shift to 10 A upon heating to 550°C.

About 7% of the samples are calcitic.

No significant differences exist between the clay mineral content of the non-red and the red sediments, although montmorillonoids seem to be more abundant in the non-red sediments.

DISCUSSION OF RESULTS

Color.—The results infer that the differences in the "red bed" coloration are due to the differences in the hematite particles as no other crystalline iron oxides are present. The work of Weiser (1935), Kennard and Howell (1941),

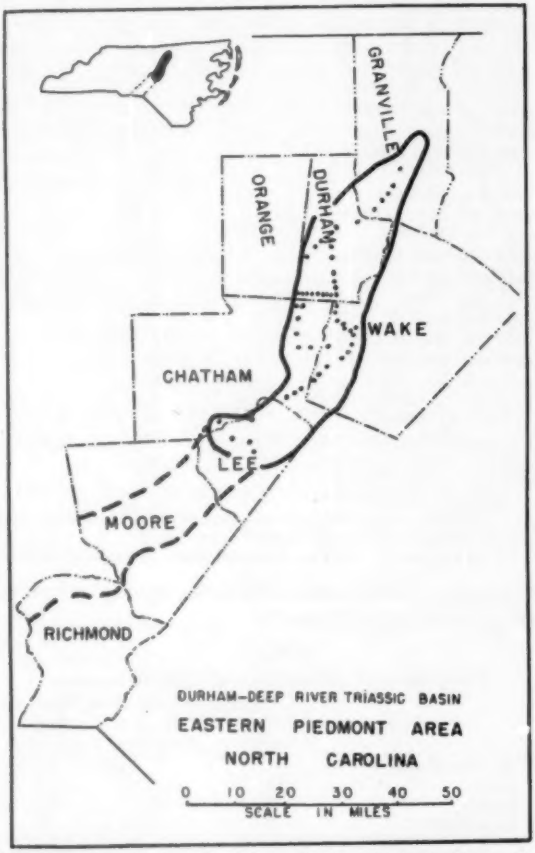

Fig. 1. Map showing the location of the Durham Triassic Basin (heavy line), the Deep River Triassic Basin (dashed line), and analyzed samples (dots).

Plice (1943, 1946), Van Houten (1948), and others has shown that hematite can be red, brown, yellow, and black depending on the particle size and the degree of agglomeration. The "red" colors might be modified by the presence of amorphous or poorly crystalline iron oxides other than hematite or by the presence of red, green, or yellow clay minerals (Grim, 1951, and Keller, 1953).

Clay mineralogy.—The clay fractions of this suite of Triassic arkosic "red bed" sediments are composed predominantly of illite and montmorillonoids. The clay minerals now present could have been formed: (1) in Triassic soils on the rocks surrounding the Durham Basin and washed into the basin, (2) by syngenetic or penecontemporaneous alteration of transported Triassic soils, (3) by epigenetic alteration of transported Triassic soils, or (4) by alteration of volcanic ash.

If these clay minerals represent eroded but unaltered mature soils, the clay mineral composition implies that the climate was somewhat dry in Newark time. The work of Alexander, Hendricks, and Nelson (1939), Winters and Simonson (1951), Jackson, et al. (1952), Knox (in Grim, 1953), and others shows that laterites are characterized by the predominance of gibbsite and/or kaolinite; red and yellow lateritic or podsolic soils, by kaolinite; typical podsolic soils, by illite with varying amounts of montmorillonoids and kaolinite; and prairie, chernozemic, and desert soils, by illite and montmorillonoids. The lack of gibbsite and the relative unimportance of kaolinite seemingly rules out the possibility that the eroded soils were mature laterites or red and yellow lateritic or podsolic soils. The iron oxides present in the Triassic sediments seemingly rule out the possibility that the eroded soils were typical podsols. The mineral association in the Triassic sediments of illite, montmorillonoids, and some calcite fits in best with the prairie, chernozemic, and desert soils of the dry or at least seasonally dry regions. It is not now possible to separate these major soil groups on the basis of clay mineralogy. Krynine (1950, p. 180) concluded that the climate of the Newark epoch in Connecticut was probably that of a tropical or sub-tropical savanna region. According to Trewartha (1943, p. 355), "Over much of the larger part of the savanna region the soil types are of the lateritic groups. . . . Toward the drier margins of the savannas . . . the prairie and chernozemic soils . . . make their appearance." Krynine found mainly kaolin, illite, and gibbsite in the clays of the Connecticut Triassic sediments, implying that the soils of Newark time were laterites or lateritic soils. The clay minerals of the Durham Basin are not those typical of laterites or lateritic soils but could represent the soils of the drier margins of a savanna region. It is difficult, however, to correlate the "red" color of the Triassic sediments with prairie and chernozemic soils.

Most probably the clay minerals now found in the Durham Basin represent unaltered transported immature soils or incompletely weathered bedrock. Evidence is plentiful to support the concept of rapid erosion during Newark time (Krynine, 1950; Prouty, 1931). It follows that much, if not most, of the eroded material came from the C-horizon. In the weathering of most silicate minerals the 2:1 clay minerals (illite, montmorillonoids, etc.) form first. Then under the proper conditions the 2:1 clay minerals alter into the

1:1 clay minerals (kaolins) and aluminum and iron oxides. Where weathering and leaching have been rather intense, the C-horizon should contain more of the 2:1 clay minerals than the A- and B-horizons; and the A- and B-horizons should contain more of the 1:1 clay minerals than the C-horizon. This is true in the lateritic soils developed on some of the granites, diorites, and basalts near Chapel Hill, N. C. Deep erosion cutting into the C-horizon of lateritic soils would explain the clay mineralogy and the "red" color of the sediments of the Durham Basin.

There is still the possibility that the present clay mineralogy of the Durham Basin sediments is explainable in whole or in part by syngenetic or epigenetic alteration. There are several possibilities in this category, but it is almost impossible to determine the quantitative importance of these possibilities. It seems unlikely, however, that syngenetic or penecontemporaneous diagenesis would be very important, as the nature of the saturating solutions in the environments of deposition (flood plains, lakes, alluvial fans, swamps) was probably chemically similar to the saturating solutions in the soils. There is a tendency for montmorillonoids to form under swampy conditions, but it is unlikely that any of the "red" samples analyzed in this work were deposited in swamps. The most probable diagenetic change is the epigenetic formation of illite from other clay minerals by the absorption of potassium from the K-feldspars in the arkosic sediments. It is difficult to decide to what extent this has occurred, but it is doubtful if it has occurred on any large scale because of the abundant montmorillonoids, which should have all changed to illite if potassium ions were plentiful, and because of the generally fresh nature of the feldspars, which implies that the feldspars have been altered little since deposition.

Finally there is the possibility that the montmorillonoids and illite represent altered volcanic ash (bentonite and metabentonite) incorporated in the Triassic sediments. This does not seem very likely because no tuffs or bentonites are known in the Durham Basin and because the presence of montmorillonoids and illite in nearly all the sediments of the Durham Basin would necessitate an almost continuous fall of volcanic ash throughout Newark time.

Most likely, then, the clay minerals of the sediments of the Durham Basin represent transported red lateritic soils, the predominate illite and montmorillonoids having come from the deeply dissected, partially weathered bedrock, and the less abundant kaolin having come from the upper, more thoroughly weathered portions of the residual mantle.

Arkosic sediments, in general, can have almost any type of clay mineral in the clay fraction, depending on the nature of the source rock, the climate and topography of the source area, and the chemical environment of the depositional site.

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RHYOLITIC TUFFS IN LOWER TERTIARY PLATEAU BASALTS OF EASTERN ICELAND*

TOMAS TRYGGVASON and DONALD E. WHITE

ABSTRACT. Three localities in eastern Iceland contain rhyolitic tuffs within the thick series of plateau basalts generally considered to belong to the North Atlantic Thulean province of early Tertiary age. Most of the tuffs were probably deposited directly as a result of nuée ardente or "glowing cloud" eruptions, but some of the tuffs at one locality were definitely reworked by streams. The basal unit of the Berufjordur tuff appears to have been compacted and somewhat welded while the deposit was still hot. No evidence for welding was found for the other tuffs.

The pyroclastic eruptions of rhyolitic pumice were probably related to much more extensive silicic rocks, including granophyre, granite, and granodiorite, that intrude the basalt flows. The evidence suggests that the silicic igneous activity was probably contemporaneous with the extrusion of the plateau basalts.

INTRODUCTION

Rhyolitic tuffs of pyroclastic origin occur within the thick series of lower Tertiary plateau basalt flows of eastern Iceland. Tuff with similar characteristics is known in three areas: the Alftafjordur (Alfta fiord) area, east of the northeastern tip of the large glacier, Vatnajokull (see fig. 1); Berufjordur, about 15 miles (24 kilometers) northeast of Alftafjordur; and Faskrudsfjordur, about 20 miles (32 kilometers) farther to the northeast. The contemporaneity of rhyolitic tuffs and plateau basalts is unusual and of petrological interest. In addition, the evidence suggests that extensive silicic intrusions of eastern Iceland are related in time and perhaps in origin to the plateau basalts.

The tuff contains foreign inclusions of altered silicic volcanic rocks derived either from the concealed pre-Tertiary basement of Iceland or, more probably, from lower Tertiary silicic intrusions.

Previous Investigations

Thoroddsen (1906, p. 277-278) mentions the existence of rhyolite on the north side of Faskrudsfjordur but does not specifically discuss the Arhofn occurrence on the shore of the fiord. Rhyolitic intrusions between Breidalur and Berufjordur and in the Alftafjordur area are described briefly.

In a study of southeastern Iceland, Cargill, Hawkes, and Ledeboer (1928) state that several localities consisting dominantly of basalt flows also contain rhyolite lavas, acid tuffs, and breccias, but these authors do not describe the extrusive rocks in detail.

Tryggvason has been interested in the silicic tuffs for several years, and has published a brief description of them (Tryggvason, 1950). Because this article is probably not available to many geologists, most of the English summary is quoted:

"A short report is given on horizons of rhyolitic breccia in the Tertiary basaltic formation in eastern Iceland. The horizons which are green by chloritization are found in three places:

1. Arhofn on the north side of Faskrudsfjordur.
2. Fagrihvammur on Berufjardarstrond (shore of the fiord, Berufjordur) where the breccia layer conforms to the in-

*Publication authorized by the Director, U. S. Geological Survey.

clined basaltic strata from the shore to the ridge of the mountain Berunestindur.

3. Flugustadadalur in Alftafjordur at the deserted farm Markusarsel where the layer is seen in the mountain some 300 m above sea level.
4. The rock fragments in the Berufjordur occurrence are rough and angular, evidently short transported whereas in the other occurrences the rock fragments are rolled to a degree. The matrix consists of rhyolitic glass from which the conclusion is drawn that the horizons in question are of effusive, volcanic origin. As the three mentioned localities are situated far apart, all three occurrences most likely represent separate centers of volcanism."

In a very recent study published while the present paper was being prepared, Dearnley (1954) recognizes the occurrence of welded tuff in the mountains near Lodmundarfjordur, about 30 miles (50 kilometers) north of Faskrudsfjordur.

Scope of the Study

The present report is a summary of field observations, largely by Tryggvason, and petrographic studies by both authors. Fagrihvammur on the north shore of Berufjordur is the only area of the three that has been seen by White. Important questions in regard to continuity and structural relations of the tuffs cannot be answered, but the available data are believed to be significant.

GENERAL GEOLOGY

Plateau Basalt Flows

East of the central belt of Quaternary volcanism (fig. 1), Iceland contains an enormous thickness of basalt flows considered to be a part of the extensive North Atlantic Thulean province of early Tertiary age (Barth, 1950). Thoroddsen (1884; 1906, p. 263-264) estimates the thickness to be at least 10,000 feet (3000 meters).

Magnificent sections of the basalt are exposed along the shores of the eastern fiords. Berufjordur, for example, trends west to northwest for more than 12 miles, aproximately perpendicular to the strike of the flows. The lavas dip 5 to 15 degrees northwest. On the southwest side of the fiord, a spectacular series of basalt flows rises abruptly to altitudes of nearly 4000 feet (fig. 1-A). Thoroddsen's estimate of the total thickness is probably very conservative.

Basalt Dikes and Silicic Intrusions

The basalt flows are cut by many basalt dikes that are commonly concentrated in swarms. Presumably, at least some were feeders for flows higher in the section. The flows are also intruded by many silicic masses, including rhyolite, granophyre, granite, and granodiorite (Cargill et al., 1928). Other intrusives are gabbro, but rocks of intermediate composition are strikingly scarce. Some of the silicic intrusions are in turn cut by basalt dikes similar in appearance to the presumed feeder dikes.

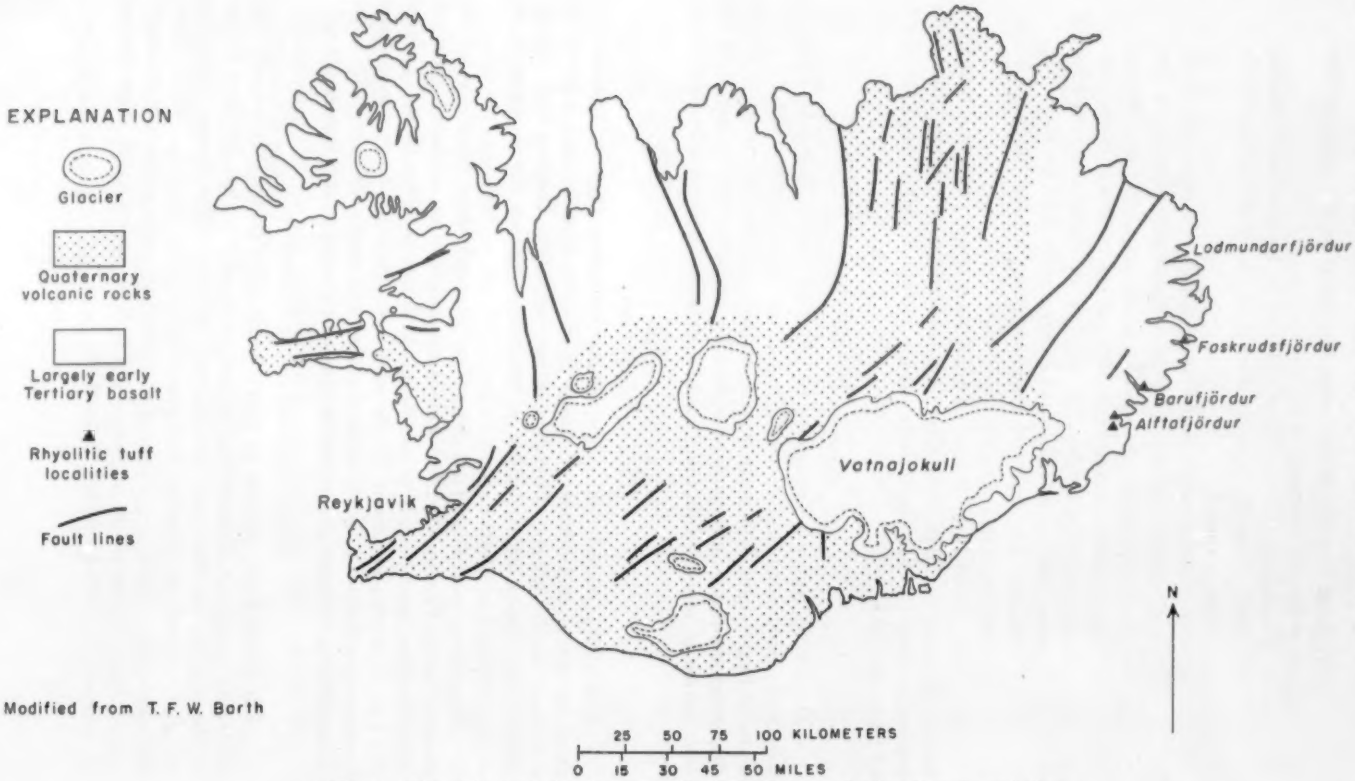


Fig. 1. Map of Iceland showing generalized distribution of volcanic rocks and rhyolitic tuff localities.

A composite dike at Straetishvarf, a few miles northeast of Berufjordur, consists of borders of basalt, each about 12 feet wide, and a core about 45 feet wide of granophyre with basalt inclusions. A mixed zone on each wall of the granophyre is about 2 feet wide. The granophyre was probably intruded before the earlier basalt had entirely solidified or cooled. A similar explanation has been proposed by Guppy and Hawkes (1925) for a composite dike on the north side of Breiddalsvik fiord about 5 miles north of Straetishvarf. Thoroddsen (1906, p. 277) has traced this dike north of Breiddalsvik for about 4 miles. Tryggvason believes the dike at Straetishvarf may be the southern continuation of the Breiddalsvik dike, and that the total length including the submarine segment is at least 9 miles.

RHYOLITIC TUFFS

Berufjordur Tuff

Rhyolitic tuff crops out prominently on sea cliffs at Fagrihvammur on the north shore of Berufjordur. It is light green, contrasting strongly with adjacent dark basalts. A short distance to the north the tuff is concealed by vegetation and possibly by marine terrace deposits to an altitude of about 200 feet above sea level. It can then be followed up the mountain to the northeast for perhaps a kilometer. It could not be distinguished visually on the slopes of intermediate altitude, as seen from the south shore of the fiord, but is again conspicuous at apparently the same stratigraphic horizon high on Berunestindur Mountain. The tuff has not been traced farther to the north, nor has it been recognized on the south side of Berufjordur.

The basalt flows and tuff dip 5 to 15 degrees northwest. The regional relationships indicate that the tuff is probably underlain by at least 4000 feet of basalt flows and is overlain by a similar or greater thickness of flows.

The basal contact is well exposed for a few feet along the beach, where the tuff rests on the somewhat irregular surface of the underlying basalt flow. The upper contact is concealed along the shore by beach deposits. The tuff appears to be completely conformable to adjacent basalt flows, although the rocks are cut by at least one fault of small displacement on the mountain slopes.

Two relatively distinct units are recognized near the beach. The lower unit (pl. 1-B and pl. 2-A) is rather coarse textured, with a thickness in the order of 35 to 40 feet, and with fragments as much as 4 inches in length. The upper unit is finer in texture with fragments seldom over half an inch in diameter and has a total thickness of at least 20 feet (pl. 2-B).

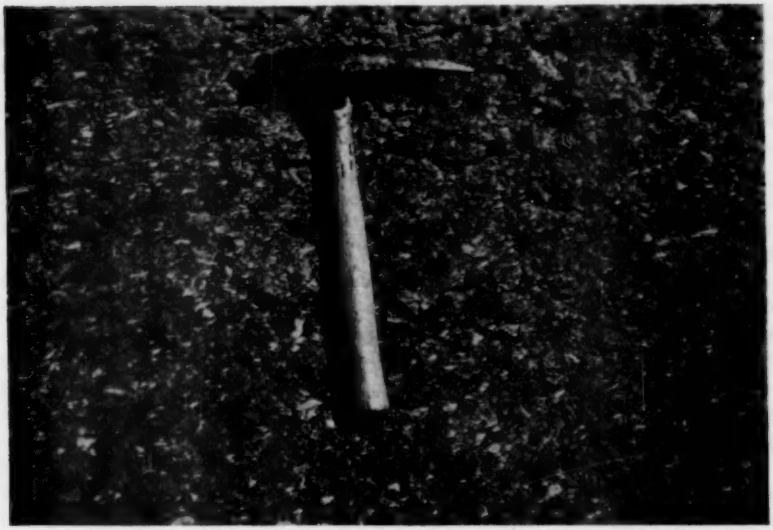
Lower unit.—The lower unit is estimated to be 35 to 40 feet thick, of which the basal 25 feet is perfectly exposed in a single cliff face (pl. 1-B). Large fragments, generally less than 2 inches long but as much as 3 or 4 inches in length are in a fine-grained light-greenish matrix. Most of the larger fragments are elongated and are oriented with their long dimensions parallel to the contacts of the unit. The tuff is unstratified, although the alinement of fragments as well as an intimate fracture system parallel to the contacts give a false impression of bedding (pl. 1-B). The average size of the fragments is about the same throughout the cliff exposure.

PLATE 1

A. View southward across Berufjordur to mountains nearly 4000 feet in altitude consisting of low-dipping basalt flows.

B. Shore exposure of the basal unit of the Berufjordur tuff. The vague, nearly horizontal planar structure has resulted from compaction and orientation of elongated fragments.

PLATE 2



A. Close-up view of Berufjordur tuff. The light-colored fragments are partly collapsed fragments of rhyolitic pumice, and the dark fragments are foreign inclusions of basalt.

B. Contact between the basal and upper units of the Berufjordur tuff. Scale shown by case of exposure meter. A few large fragments characteristic of the basal unit occur in the lower part of the upper unit.

Most of the large fragments are rhyolitic in composition, are light in color, ranging from white to light red and buff, and have a dull porcelanic appearance. Phenocrysts are generally lacking, but a few plagioclase crystals may be found. An inconspicuous internal banding is characteristic of these fragments and is parallel to their long dimensions and to the contacts of the tuff. Other fragments are brown to black and consist of basaltic rocks. They are commonly nearly equidimensional, but elongated fragments are generally oriented parallel to the contacts.

The specific gravities of two specimens of tuff from the lower unit are 2.23 and 2.14. The higher density sample was obtained about 5 feet above the base of the unit, but the stratigraphic position of the other sample is not known.

Upper unit.—The upper unit, estimated to be at least 20 feet thick, is somewhat similar to the basal unit except that the fragments are rarely more than half an inch in diameter, and the matrix is greenish gray. Internal stratification is absent, but platy fractures are parallel to the contacts. The spacing of the fractures ranges from an inch to 2 inches apart. Specific gravities of two specimens from the upper unit are 2.06 and 2.10. The precise stratigraphic position of neither is known.

The contact between the two units is well exposed for only a few feet along the shore. This contact, shown in plate 2-B, is rather sharp, although a few large fragments characteristic of the lower unit may be seen in the basal few inches of the upper unit. No evidence was found for an erosional break or for stream action at the contact.

Petrography.—Thin sections of the tuff reveal two distinct types of silicic fragments as well as particles of basalt and less abundant components in a fine-grained matrix. This matrix originally consisted of small fragments of pumice, but alteration and probably welding have destroyed all but a few shardlike outlines. The dominant type of light-colored fragment (table 1, no. 22a) consists of pumice and collapsed pumice containing rare phenocrysts of clear oligoclase (An_{25}) as much as 0.4 mm in diameter, many small alined oligoclase laths averaging about 0.1 mm in length, and a few small tabular crystals of potash feldspar (sanidine?). Phenocrysts of quartz and dark minerals are completely absent. The original vesicles range from 0.04 to 0.1 mm in diameter and are lined with dark green chlorite. A few are entirely filled with chlorite, but most contain zeolite cores. The zeolites are believed to be analcite and probably chabazite. The original vesicles in parts of most fragments are collapsed and are now represented by short narrow bands of light green chlorite, generally oriented parallel to the length of the fragment. The alined bands of chlorite are the cause of the banding apparent in hand specimen.

The original glass of the pumice is altered at least in part to analcite (?), with very low birefringence and with indices between 1.48 and 1.49. An isotropic substance with index of refraction a little above 1.49 may be unaltered glass.

Light-colored fragments other than pumice are difficult to distinguish megascopically but are conspicuous under the microscope. These fragments consist of altered silicic volcanic rocks as much as 3 mm in diameter.

TABLE 1

Components of some Rhyolitic Tuffs of Eastern Iceland

(All fragments less than 0.1 mm in diameter are included in the matrix. Determined by D. E. White, Chayes point-counter method.)

	22a	*22b*	*213*	*468*	*469*
Components in percent, including matrix					
Matrix	47.2	77.2	49.7	42.6	56.9
Rhyolitic pumice	31.9	16.2	35.4	26.7	21.7
Plagioclase phenocrysts	.4				
Basalt	11.1	2.8	8.4	18.4	10.6
Silicic inclusions	7.3	1.0	6.0	7.6	7.2
Plagioclase crystals	1.4	2.8	.4	3.9	3.4
Pyroxene crystals	.1	.1		.2	.2
Vein quartz	.5		.1	.1	
Granophyre				.5	
Total	99.9	100.1	100.0	100.0	100.0
Components in percent, excluding matrix					
Rhyolitic pumice	61.4	70.9	70.3	46.5	50.4
Basalt	21.2	12.2	16.7	32.1	24.6
Silicic inclusions	13.8	4.3	11.9	13.2	16.8
Plagioclase crystals	2.6	12.2	.9	6.8	7.8
Pyroxene crystals	.1	.4		.3	.4
Vein quartz	.9		.2	.2	
Granophyre				.8	
Total	100.0	100.0	100.0	99.9	100.0

22a.—Berufjordur tuff, lower unit, collected 5 feet above base. Specific gravity 2.23. Maximum length of fragments in hand specimen, 2 cm; in thin section, 8 mm.

22b.—Berufjordur tuff, upper unit, collected from near middle of unit. Specific gravity, 2.06. Maximum length of fragments in hand specimen, 5 mm; in thin section, 2 mm.

213.—Faskrudsfjordur tuff. Maximum length of fragments in thin section, 4 mm.

468.—Markusarsel tuff, the uppermost coarse green unit. Specific gravity 2.16. Maximum length of fragments in thin section, 3 mm.

469.—Markusarsel tuff, an upper green layer, probably below 468. Maximum length of fragments in thin section, 4.5 mm.

In detail, these fragments show a considerable variety of relict textures, but the original textures were all fine grained, and dominantly felsitic to trachytic. Large phenocrysts are almost completely absent, but a few tabular plagioclase phenocrysts were seen, in part replaced by zeolite. Ferromagnesian phenocrysts were definitely absent except for some probable hornblende needles, now entirely altered. The groundmass consists dominantly of a fine-grained mosaic of interlocking crystals of quartz and albite. Optical continuity is apparent in patches as much as 0.3 mm in diameter. In some fragments the patches show random extinction under crossed nicols, but the fragments with trachytic texture commonly show preferred extinction positions for a majority of the patches. The texture and composition of the groundmass probably result from hydrothermal replacement rather than devitrification. This suggestion may be supported by the presence of a few quartz veinlets in some fragments, and cubic opaque crystals believed to be hematite after pyrite, in other fragments.

Dark fragments of basalt are next in abundance to the pumice (table 1). A considerable variety of textures was recognized, but none were studied in detail. The fragments are foreign to the silicic tuff and were probably derived from the thick plateau basalts through which the tuff was erupted. A few fragments contain large plagioclase phenocrysts, and a very few contain prominent augite.

Broken or fractured crystals of plagioclase as much as 0.3 mm in diameter occur separately in the matrix of small pumice fragments. The composition of most of the plagioclase is approximately An_{25}, similar to the phenocrysts of the pumice fragments; but some is as calcic as An_{50}. The plagioclase generally shows some zoning but twinning is not abundant. Some fragments are untwinned, and a few also show no cleavage or zoning, and are distinguished from quartz with difficulty. Most crystals are fresh, but a few show incipient replacement by zeolite.

A few fragments consist of interlocking crystals of strained quartz, some of which show euhedral growth lines, and were probably derived from quartz veins or veinlets. A few euhedral crystals of augite occur in the tuff. The origin of the augite is not clear because none of the major rock types composing the fragments is known to contain similar augite. Some of the crystals have a slight bluish color and may be a soda-bearing variety.

The matrix of the larger fragments is dominantly material similar in composition to the pumice. Individual small fragments are generally not clearly distinguishable in this matrix, but a few have shardlike outlines. Some of the original glass may be preserved, but much is now analcite(?). Secondary minerals are chlorite, montmorillonite(?), and celadonite.

The pumice fragments and the matrix of the lower unit appear to have been compacted and welded to adjacent fragments at the time the tuff was erupted, although the existence of many uncollapsed vesicles indicates only partial compaction and probably incomplete welding. Primary welding is difficult to prove in tuffs that have been altered, and incipient welding is particularly difficult to recognize with certainty. The most that can be said for the lower unit is that it was probably welded.

A thin section of the upper fine-grained unit of the tuff contains essentially the same components as the basal unit, but the modal analysis indicates that the proportion of the components is considerably different in the two units (table 1, 22a and 22b). If these thin sections are representative of the average of the two units, the contrasting proportions cannot be explained entirely by the finer average size of the fragments of the upper unit. Rhyolitic pumice is more dominant in the fragments of the upper unit than of the lower and is also belived to be more abundant in the matrix. Separate oligoclase crystals are also relatively more abundant in the upper unit. This suggests that these phenocrysts are somehow directly related to the source magma for the tuff eruption in spite of the fact that oligoclase phenocrysts are relatively scarce in pumice fragments.

Faskrudsfjordur Tuff

Green tuff similar to that of Berufjordur is found on the north side of Faskrudsfjordur. The tuff crops out in Arhofn Creek and for a hundred feet or more along the shore of the fiord. The rocks are characterized by a platy fracture system and by somewhat more intense alteration and weathering than is apparent in the Berufjordur tuff. Fragments of pumice and basalt are prominent but rarely exceed an inch in diameter.

Petrography.—The components of a thin section (no. 213) of the Faskrudsfjordur tuff have been determined quantitatively and are compared in table 1 with specimens of the upper and lower units of the Berufjordur tuff. The coarse-grained tuffs of Berufjordur and Faskrudsfjordur are strikingly similar in composition, and are much more alike than are the two Berufjordur units.

The detailed petrography of the two coarse-grained tuffs is so similar in most respects that only the contrasting features of the Faskrudsfjordur tuff will be mentioned. The pumice fragments show little evidence of collapse or of welding. Alteration is a little more pronounced, with abundant zeolites and common chlorite and celadonite(?). A few cavities are filled with quartz, and calcite is locally abundant.

Several fragments of basalt appear to be rounded chilled lapilli with fine-grained borders and with large crystals and vesicles in the cores. Two or three fragments of the silicic volcanic inclusions contain narrow quartz veinlets, and the fine-grained mosaic of the groundmass is dominantly albite with some quartz. A single euhedral quartz crystal was found. It is similar in general appearance to the occasional untwinned and unzoned plagioclase fragments except for its crystal form and its uniaxial positive interference figure. One small crystal of olive-green to brownish-green hornblende was also identified.

Plagioclase phenocrysts and crystal fragments are relatively rare. Although most of the plagioclase is very fresh, parts of many crystals are replaced by zeolite and a few now consist entirely of zeolite.

Recognizable glass shards are abundant in the matrix, and are much better preserved than in the Berufjordur tuff, in spite of the fact that alteration and replacement is a little more extensive in the Faskrudsfjordur tuff.

Alftafjordur Tuff

The thickest and most extensive of the tuffs described in this paper occurs in the mountains west of Alftafjordur. The tuffs are conformable to the adjacent basalt flows, all of which dip 5 to 10 degrees west. The tuff crops out west of a deserted farm called Markusarsel in the floor of the valley Flugustadadalur. Although the tuff has not been found in place on the south side of the valley, boulders of tuff indicate its presence. The tuff has been traced visually to the north from Flugustadadalur to the north side of the valley Geithellnadalur, a distance of about 7 miles. Its extent farther to the north is not known. Only the rocks at Markusarsel and in Geithellnadalur have been examined in outcrop.

Field observations and sampling of the tuff are rather incomplete and do not permit a thorough description. Its total thickness has not been measured,

but is estimated by Tryggvason to be in the order of 300 to 500 feet. The thickness decreases gradually to the north, but is still appreciable in Geithellnadalur. Several different beds make up the sequence. Coarse-textured light-green layers are separated by fine-grained strata more earthy in appearance and generally somewhat darker in color.

Markusarsel locality.—At Markusarsel three green coarse-grained beds are particularly resistant to weathering and are therefore conspicuous features of the landscape. These beds are separated by finer-grained strata.

The basal bed is in many respects similar to the lower unit at Berufjordur. However, the color is somewhat darker, and the pumice and basalt fragments are on the average somewhat coarser. Internal stratification is absent, and elongated fragments are generally oriented parallel to the contacts as in the Berufjordur tuff.

The middle and upper strata are not so coarse grained as the basal stratum, and basaltic fragments are not so prominent. Only a few fragments are larger than an inch in diameter. The upper bed shows crude internal stratification.

Petrography of Markusarsel rocks.—The components of the uppermost tuff bed (no. 468) are shown in table 1. The thin section shows definite stratification, with several laminae consisting largely of sorted fragments more than 0.1 mm in diameter and another with few fragments larger than 0.1 mm. None of the fragments is rounded but some are subangular.

Most of the identifiable fragments are similar to those of the tuffs described previously, but the proportions are somewhat different. Basalt and altered silicic fragments together are approximately equal in number to the pumice fragments, in contrast to the great dominance of pumice in the other tuffs.

Of particular significance is a single fragment of granophyre. Its texture is similar to, if not identical with the texture of some of the granophyres that intrude the basalt flows of southeastern Iceland. Euhedral plagioclase crystals and rare subhedral to anhedral quartz crystals are contained in a dominant matrix consisting of a micrographic intergrowth of plagioclase and quartz.

Other components are broken plagioclase crystals, several bluish-green augite crystals, fragments of vein(?) quartz, several small clastic zircon crystals, and a single fragment of microcline.

The rock shows considerable hydrothermal alteration. Zeolites (heulandite and stilbite?) are abundant replacements of pumice and plagioclase crystals and occur as cavity fillings. A little albite also replaces the original oligoclase-andesine of the plagioclase. Celadonite and chlorite are also common.

Specimen 469 is also from the upper part of the Markusarsel tuffs but is overlain by the tuff that has just been described. The components are similar to those of the other tuffs, but the proportions are intermediate between those of the water-laid tuff of no. 469 and the unstratified tuffs. Shard structure is abundant and well preserved in most of the glass fragments of the groundmass.

The plagioclase (oligoclase-andesine) is less altered than in no. 468, but most crystals show a little replacement by zeolite, which is also abundant in

amygdules of the pumice and in spaces between fragments. Chlorite also occurs in the amygdules.

The tuff of specimen no. 469 is pyroclastic in origin and does not appear to be reworked by streams. No evidence was found, however, for compaction or welding while still hot.

A thin section of one of the fine-grained strata separating two coarse greenish layers consists largely of tiny glass shards and other clastic fragments replaced to a considerable extent by zeolite and some chlorite.

Geithellnadalur locality.—Alftafjordur tuff at Markusarsel can be traced north 7 miles to Geithellnadalur. In thin section the rocks consist largely of fragments of basalt, but other fragments are probably pumice and altered silicic volcanic rocks similar to the fragments of previously described tuffs. The coarse-grained tuff is violet and is considerably more altered than other rocks. Because the original nature of many of the fragments is uncertain, a quantitative determination of fragment proportions was not attempted. Many red-brown crystals appear to be iron oxide pseudomorphs of pyrite. Zeolite is abundant and is perhaps dominantly stilbite.

One of the darker fine-grained strata consists largely of basalt fragments, but a few particles of pumice and altered silicic volcanic rock are believed present. A single fragment of granophyre was identified in thin section, similar to the granophyre fragment of no. 468. Most of the fragments are 0.3 to 1 mm in diameter, are angular to subrounded, and were definitely sorted and deposited by streams.

ORIGIN OF THE RHYOLITIC TUFFS

Much of the tuff of eastern Iceland was a direct product of pyroclastic eruptions and consists of thick strata of airborne pumice, probably deposited from "glowing clouds." The Berufjordur and Faskrudsfjordur tuffs, and probably the Alftafjordur tuff layers without internal stratification, are of this type. The basal unit at Berufjordur was probably compacted and welded to some extent while it was still hot, but the evidence is not conclusive. No definite evidence was found for primary welding of the other tuffs.

Some of the Alftafjordur tuffs were reworked by streams and show some sorting and internal stratification. These tuffs also contain more basalt fragments than the tuffs deposited directly from pyroclastic eruptions.

The interrelationships and relative ages of the described tuffs are not known. Presumably the deposits of the three principal areas are distinct and were produced from separate eruption centers, but the possibility of contemporaneity has not been eliminated. The petrographic similarities of the Berufjordur and Faskrudsfjordur tuffs are particularly striking. Detailed mapping of stratigraphy and structure will be necessary to determine the relationships. All the tuffs, however, have a common source in rhyolitic volcanism that occurred during the period of extrusion of plateau basalts.

During the summer of 1952, G. Kjartansson and Tryggvason found a very large rhyolitic intrusion in the mountains about 6 miles south-southwest of Alftafjordur. Tryggvason suggests that the Alftafjordur tuff, which thickens southward from Geithellnadalur to Markusarsel, may be an extrusive phase of the large rhyolite intrusion.

The rhyolitic tuffs are probably related genetically to the silicic intrusions of eastern Iceland. Two fragments of granophyre were found in thin sections of Alftafjordur tuff, indicating that granophyre had existed before eruption of the tuff.

The altered silicic volcanic inclusions in the tuff were derived either from the pre-Tertiary basement rocks, or from lower Tertiary silicic volcanic rocks. The inclusions were probably altered hydrothermally before the eruption of the rhyolitic tuff. Although conclusive evidence is lacking, the inclusions may have been derived from rhyolite or perhaps granophyre intrusions. The granites and granodiorites may also be phases of the same silicic igneous activity, perhaps intruded after a thick cover was provided by the piling up of plateau basalt flows.

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STUDIES IN THE MICA GROUP; X-RAY DATA ON ROSCOELITE AND BARIUM-MUSCOVITE

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ABSTRACT. X-ray data have been obtained for several micas previously regarded as varieties of muscovite. It was found that the chemically distinct roscoelite and the barium mica from Franklin, New Jersey, have the 1-layer monoclinic (1M) mica structure and therefore can not be regarded as varieties of the common 2-layer monoclinic (2M) muscovite.

INTRODUCTION

During the course of investigations initiated as part of University of Michigan Engineering Research Project M-978, Natural Mica Studies, sponsored by the United States Army Signal Corps (Heinrich, et al., 1953), and also continued subsequently as well at The Ohio State University, a number of rare micas that have usually been considered as varieties of muscovites were examined. These include the barium-muscovite of Bauer and Berman (1933) and a number of roscoelites. These investigations have produced new data on these imperfectly known minerals.

The writers acknowledge with deep appreciation loans of specimens from the Harvard Mineralogical Museum, the United States Geological Survey, and the United States National Museum. The writers are grateful to Professor Duncan McConnell, Ohio State University, for reading the manuscript, and to Dr. S. Benedict Levin, Deputy Chief, Chemical Physics Branch, Squier Signal Laboratory, under whose direction project M-978 was administered. Mrs. E. G. Smith, Mr. D. W. Levandowski and Mr. C. H. Hewitt assisted in various parts of this study.

ROSCOELITE

Roscoelite has been generally accepted as a vanadiferous muscovite in which V has replaced much of the Al. This conclusion was reached by Clarke on the basis of the chemical analyses of Hillebrand (Hillebrand, Turner and Clarke, 1899). A detailed study of the optical properties of roscoelite was made by Wright (1914), in which the similarities to muscovite, such as the position of the optic plane normal to (010), were noted. Atomic ratios calculated by Wells and Brannock (1946) on the basis of ten chemical analyses show that the sum of V and Al (with the exception of the Al required to fill tetrahedral positions) is two atoms, as is required for octahedral coordination in the sheet of a heptaphyllite (muscovite-type) mica.

The first published results of X-ray work on roscoelite found in the literature are embodied in a statement in Fischer (1942, p. 376-377): "The principal vanadium mineral is micaceous, and it has heretofore been thought to be roscoelite, the vanadium mica; but as a result of recent x-ray studies by Sterling Hendricks of the Department of Agriculture, it is now thought to belong to the imperfectly understood hydrous-mica group of clay minerals." This tentative statement apparently has been widely accepted, and the micaceous vanadium mineral of the Colorado Plateau area subsequently has been referred to as vanadium hydromica by geologists studying these deposits. Since the results of our study on roscoelite were not in agreement with this

identification, Dr. Hendricks was contacted for further details. In his reply he states: "The sample used was an extremely small one (actually too small to work with) and the powder diffraction photographs were poor. The statement was based on an apparent value of d(001) in excess of 10.0Å." Studies by Fischer (1937, p. 929) seem to indicate the presence of another vanadiferous micaceous mineral, possibly of chloritic nature, in the vanadium ores of the Placerville district of Colorado. The only other reported structural work is a statement in Wells and Brannock (1946, p. 121) attributed to J. M. Axelrod, which indicates that X-ray powder patterns of roscoelite have "lines very close to those of muscovite, paragonite, and biotite."

In the collections of the University of Michigan only a few fine-grained samples of roscoelite were available, so that the study was begun by means of the powder method. Powder photographs were taken of three specimens from California localities. All of these have spacings that correspond closely with those of the 1-layer monoclinic (1M) mica polymorph; muscovite usually has a 2-layer monoclinic (2M) structure. Powder photographs of type material from the Stockslager mine (obtained from the U. S. National Museum and from the Harvard Mineralogical Museum) also gave the 1M pattern. On a single flake suitable for Weissenberg study from this locality, a zero-level, a-axis photograph indicated the presence of the 1M structure, and the optic plane was found to be parallel with the (010) pinacoid. Samples of two recently analyzed roscoelites, one from Paradox Valley, Colorado (Wells and Brannock, 1946), and the other from the Placerville District, Colorado (Fischer, Haff, and Rominger, 1947) were obtained from Mr. Axelrod. These samples are the same one on which his measurements were made (Wells and Brannock, 1946, p. 121). Powder photographs of these specimens likewise gave 1-layer patterns (and a few weak quartz lines) with no values of d(001) in excess of 10.0Å.

The d-spacings for two roscoelites are listed in table 1 and are compared with spacings for 1M lepidolite. All are very similar, but the roscoelite spacings are in most cases slightly larger than corresponding 1M lepidolite spacings. Two slightly different types of roscoelite powder patterns, having intensity differences, were obtained. Specimens of California roscoelite are of one type whereas those from Paradox Valley and the Placerville District, Colorado yield the other. The measurements of one powder pattern representative of each type are presented in table 1. Figure 1 illustrates both types, as well as a powder pattern of common 2M muscovite. It shows that the roscoelite patterns, although they vary slightly among themselves as far as intensities are concerned, have entirely different spacings from the common 2-layer muscovite.

Several other occurrences of roscoelite or vanadium-bearing muscovite have been reported in the literature but only for the vanadiferous muscovite (1.08 percent V_2O_3) from Schmiedefeld, Germany described by Jung (1937) have any X-ray data been recorded. This mica appears to have the normal 2M structure, as is shown by his X-ray powder spacings (p. 40).

TABLE 1
X-ray Powder Data

1. 1M lepidolite		2. Roscoelite		3. Roscoelite		4. Ba-Muscovite	
d(Å)	I	d(Å)	I	d(Å)	I	d(Å)	I
9.98	MS	10.0	VS	10.0	VS	9.98	S
4.98	MS	- -		5.01	W	4.98	VW
4.53	M	4.55	MS	4.54	S	4.48	S
4.34	VW	4.39	MW	4.39	VW	- -	
4.12	VW	4.15	W	4.13	VW	4.12	VVW
3.86	VW	3.91	VW	3.91	W	3.86	VVW
3.62	S	3.66	S	3.66	M	3.62	MS
3.33	VS	3.34	VS	3.35	S	3.31	S
3.07	S	3.11	S	3.11	M	3.07	MS
2.86	M	2.89	W d	2.90	MW	2.85	VVW
2.68	W	2.69	M	2.70	W	2.69	VVW
2.58	S	2.60	MS	2.60	S	2.56	VS
2.48	W	2.42	M	2.42	M	2.46	W
2.39	MW	2.35	M	- -		2.39	MW
2.26	W	2.28	W	2.28	W	- -	
- -		2.22	VW	2.21	W	2.22	W d
2.14	MW	2.16	W	2.16	M d	2.14	M
- -		2.03	VW	- -		- -	
1.99	MS	2.00	W	2.00	M d	1.99	M
1.96	VVW	- -		- -		1.96	W
1.72	VW	1.73	VW	1.72	VW	1.72	VVW
1.65	M d	1.66	M	1.67	MW d	1.65	M d
1.58	VW	1.60	VW	- -		- -	
1.51	S	1.52	MS	1.52	MS	1.50	S
1.43	VW	1.44	W d	1.44	VW d	1.42	VVW
1.38	VW	- -		1.38	W	- -	
1.35	VW	1.35	W	1.35	W	1.35	W d
1.34	W	- -		- -		- -	
1.30	M	1.31	MW d	1.31	W d	1.30	M d
1.25	VW	1.26	W	1.26	W	1.25	W

1. 1-layer monoclinic lepidolite, Brown Derby Pegmatite, Colorado.
2. Roscoelite, Stockslager Mine, California. U.S.N.M. no. 84451.
3. Roscoelite, Paradox Valley, Colorado; described by Wells and Brannock (1946). Spindle for powder photographs supplied by Mr. J. M. Axelrod.
4. Barium-muscovite, Franklin, New Jersey; described by Bauer and Berman (1933). U.S.N.M. no. 105848.

All specimens studied by means of filtered copper radiation.

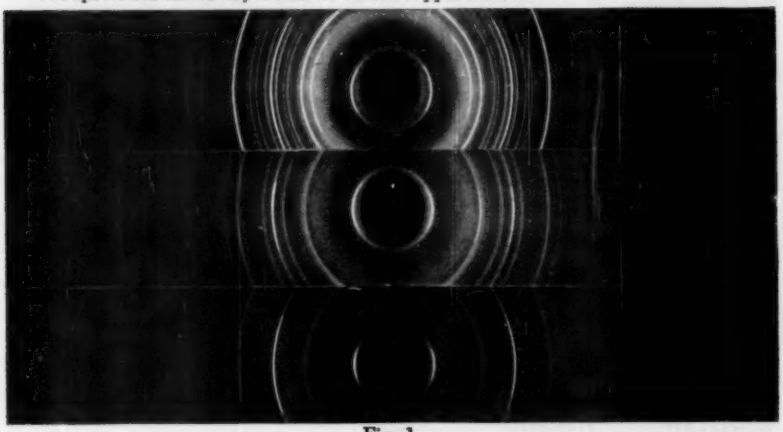

Fig. 1.
Top: Common 2-layer (2M) muscovite, Varuträsk, Sweden.
Middle: 1-layer (1M) roscoelite, Stockslager Mine, California.
Bottom: 1-layer (1M) roscoelite, Placerville District, Colorado.
All photographs with filtered copper radiation.

Apparently the normal 2M muscovite structure can accommodate the substitution of small amounts of V for Al without any appreciable change. Those micas which have been shown to have the 1M roscoelite structure contain approximately 17 percent V_2O_3 or more, suggesting that this structural change accompanies the large-scale substitution of V for Al. Since roscoelite is both chemically and structurally distinct from other muscovites, it can no longer be regarded as a vanadiferous muscovite, but must be given the status of an independent species.

BARIUM-MUSCOVITE

A micaceous mineral with 9.89 percent BaO, from Franklin, New Jersey, described by Bauer and Berman (1933) has been called barium-muscovite. Muscovites with substantial amounts of barium have also been called oellacherite. Specimens of the Franklin material were obtained from the Harvard Mineralogical Museum and from the U. S. National Museum (no. 105848). All specimens are massive and pink in color. The formula, as calculated from Bauer's analysis, is in close agreement with the requirements for a muscovite-type mica. Microscope examination demonstrates the essential homogeneity of the material from the U. S. National Museum. It consists of exceedingly small flakes that form a colorless intergrowth. Petrographic examination of the material obtained from the Harvard Mineralogical Museum shows the mica to be an alteration product of a feldspar, and the two minerals are intimately intergrown. X-ray powder photographs of the Harvard specimens show strong feldspar contamination, whereas the U.S.N.M. material is free from contamination. The structure as determined from the powder patterns of the U.S.N.M. material is not that of the normal 2M muscovite. It is considered to be 1-layer monoclinic (1M) on the basis of the similarity to 1M roscoelite and lepidolite spacings (table 1). No single crystal studies were feasible owing to the extremely fine-grained nature of the mica. If the feldspar is hyalophane, this would account for the availability of the Ba reported in the mica; otherwise the Ba could have been introduced hydrothermally.

Because this barium mica is both structurally and chemically distinct from other micas, it can no longer be considered a variety of normal muscovite, but must be given the status of an independent species. Since, however, it is known only imperfectly still and but from one locality, it does not seem fitting now to give this mineral a special name; barium mica should suffice. Normal 2M muscovite can undoubtedly accommodate small amounts of Ba, but apparently the large-scale substitution of Ba for K requires the crystalline rearrangement to the 1M structure. The situation is analogous to that of roscoelite.

Kultiassov and Dubinkina (1946) have described a vanadium-bearing variety of oellacherite from the Karatau, U.S.S.R. vanadium deposits. This mineral is interesting in that it is chemically similar to both roscoelite and the Franklin barium mica and also because it is the only barium mica found in the literature for which X-ray data are reported. Three varieties of the mineral are distinguished:

1. Light green, silky, fibrous aggregates, intimately intergrown with columnar quartz.
2. Dark green, pearly tablets imbedded in coarse quartz veins.
3. Dark grayish-green flakes and scales on fault surfaces.

Chemical analyses of the three varieties show similarities to oellacherite with respect to the BaO content and to roscoelite with respect to the V_2O_3 content:

	1.	2.	3.
V_2O_3	6.18	17.92	16.44
BaO	7.15	5.27	7.20

X-ray powder data are given for the fibrous and flaky varieties (1 and 3). Inspection of the d-spacings reported for the fibrous type indicates the presence of considerable quartz. Practically all the spacings and comparable intensities listed on the A.S.T.M. card for quartz are recorded. When these lines are subtracted from the list of d-spacings, only weak reflections remain. No mica polymorph with these remaining spacings could be definitely identified. The reported spacings for type 3 are equally difficult to interpret. Although most lines do correspond to the general mica spacings, their assignment to a definite mica polymorph does not seem possible at present. In view of this information, further study is needed in order to definitely establish the relationship between this mineral and other members of the mica group.

An attempt was made to obtain specimens of oellacherite from other localities for X-ray studies. The only specimen available was originally from the type locality (Pfitschthal, Tyrol) and was borrowed from the Harvard Mineralogical Museum. X-ray studies show that it has crystallized with the 2M muscovite structure. However, a flame test for Ba gave negative results and, therefore, the validity of this specimen is in doubt.

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CLIFF RETREAT IN THE SOUTHWESTERN UNITED STATES

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ABSTRACT. Studies of escarpments developed in nearly horizontal rocks of various characteristics in the southwestern United States show that slope angles vary within a surprisingly limited range, depending upon the angle of repose and angle of sliding friction of the materials involved; that scarp retreat is a discontinuous process consisting of sudden rock falls separated by long periods of stability during which sliderock is gradually removed; that active retreat takes place only when these sliderock accumulations can be removed; and that retreat of the escarpment is by formation of successive parallel cliffs and slopes.

INTRODUCTION

The problem of cliff development and retreat has been the subject of intermittent study by the author since 1941. Several facets of this problem have been particularly puzzling, including the exact mechanism by which retreat occurs, the influence of various rock types on cliff forms, the reasons for the similarity of forms developed in diverse rock types, reasons for variability in location of the boundary between cliff and basal slope, and cause of certain minor slope forms.

The present study is part of a coordinated research program of quantitative analysis of erosional landforms supported by the Office of Naval Research, Geography Branch contract N6 ONR 271, Task Order 30, with Columbia University, Professor A. N. Strahler Project Director.

In this report the general term "scarp" or "escarpment" is defined as the compound form consisting of one or more vertical or nearly vertical cliffs, and one or more slopes either bare rock or sliderock-covered at some angle distinctly less than the cliff angle. The typical escarpment in the Southwest consists of an upper cliff of variable height, comprising 10 to 75 percent of the total height of the escarpment, and a lower slope, comprising 25 to 90 percent of the total height of the escarpment.

Areas selected for study include parts of the Southwest in which escarpments of large size have been developed in a variety of horizontal or nearly horizontal rock types. Representative examples are shown in figures 1-3, and plate 1.

FIELD OBSERVATIONS

Observations made at each locality include: angle of talus slope (talus angle), angle of bare rock slope below the cliff (rock slope angle), height of escarpment, height of cliff, length of slope, character of cliff-making formation, character of slope-making formation, character of talus blocks, thickness of sliderock cover, where visible, and angle of sub-talus slope, where visible.

The last two observations, while of considerable significance, could not be made in every case and hence are not included in the tables. Thickness of sliderock cover varied from 2 or 3 inches, equivalent to one layer of sliderock blocks, to 15 feet, but averaged about 3 to 6 feet, somewhat thinner than anticipated. The angle of sub-talus slopes ranged from 26 to 36°.

Five principal types of cliff-making formations and five principal types of slope-making formations were recognized. The data for these types are summarized in figure 4 and tables 1 and 2. The talus angle is essentially the angle of repose for the material involved; the rock slope angle is essentially the angle of sliding friction (Van Burkalow, 1945).

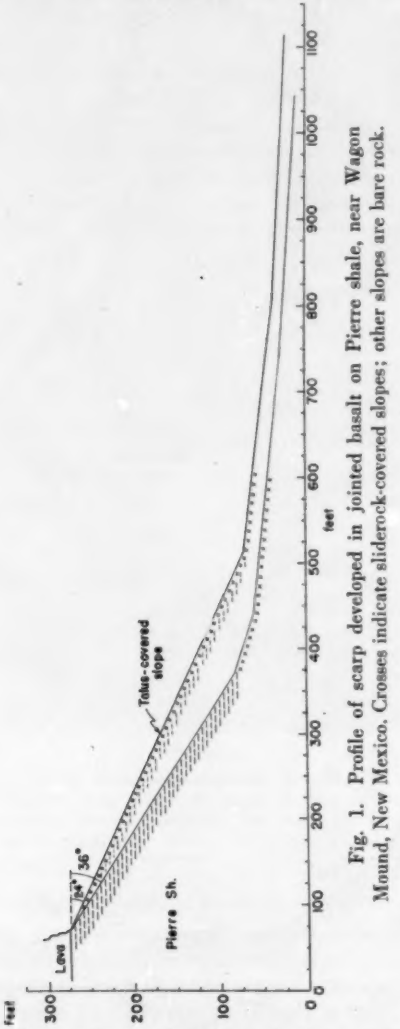

Fig. 1. Profile of scarp developed in jointed basalt on Pierre shale, near Wagon Mound, New Mexico. Crosses indicate sliderock-covered slopes; other slopes are bare rock.

In order to test the conclusion that the rock slopes were actually the slopes of sliding friction, a laboratory model was constructed consisting of an adjustable inclined plane which could be surfaced with different materials,

including unfinished sandstone slab and various grades of sandpaper selected for their textural similarity to the exposed rocks of bare slopes. The results of experiments with fragments of different materials, including sandstone, limestone, shale, conglomerate, basalt, and granite, are given in figure 4. The mean sliding angle of all types of material is 35°. Presence of a thin sheet of running water on the inclined plane produced no significant change in the angle of sliding friction. Agreement of field observations and laboratory experiments is very close.

Reference to figures 1-3 and tables 1 and 2 shows that the talus angle is always less than the angle of sliding friction in the areas studied. This contradicts the findings of Van Burkalow (1945, p. 703-705). Disagreement of field and laboratory data is to be expected in this case, since natural slide-rock accumulations do not consist of precisely screened material and have been exposed to the action of weathering for a considerable period of time. Whereas creep may reduce a talus angle below the angle of repose, it cannot similarly affect a bedrock slope.

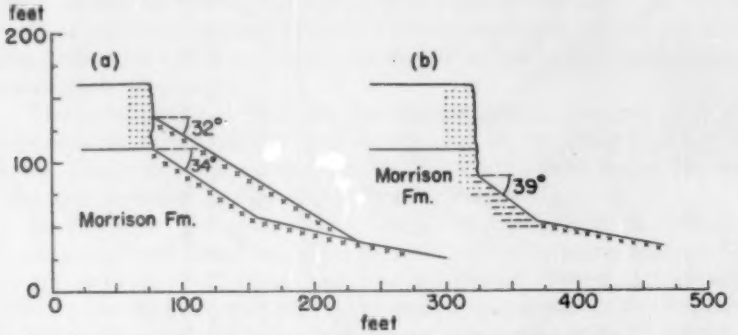

Fig. 2. Profiles of escarpments developed in the Morrison formation, near Rito, New Mexico. Angles and relations of cliff to slope are characteristic.

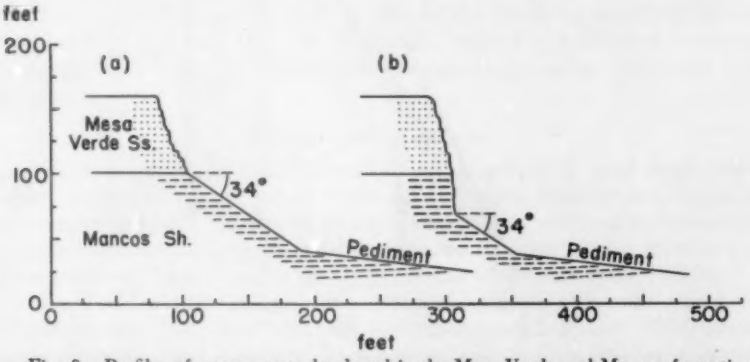

Fig. 3. Profiles of escarpments developed in the Mesa Verde and Mancos formations, near Shiprock, New Mexico. No sliderock cover present, and the position of boundary between cliff and slope varies widely. See also plate 1.

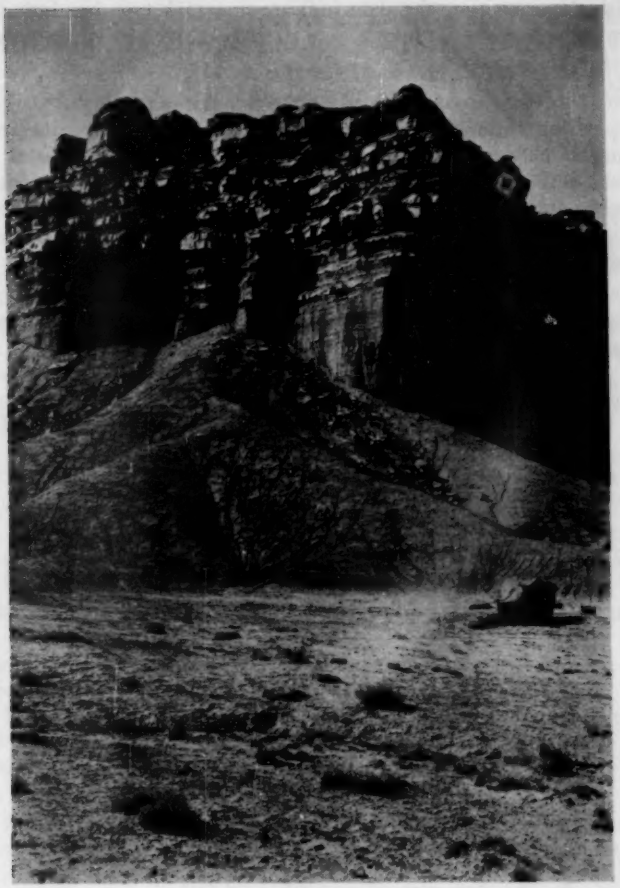

PLATE 1

Southeast corner of Table Mesa, near Shiprock, New Mexico. Mesa Verde formation above, Mancos shale below. Note the wide range in contact between cliff and slope, showing no relation to variations in resistance. The slopes are devoid of sliderock cover, except for the small accumulations of rubble in the center and near left edge of view. Photo by A. N. Strahler.

INFLUENCE OF ROCK TYPE ON SLOPE FORM

Talus and rock slope angles have a high degree of uniformity with one exception. The mean of talus angles measured below a cap rock of columnar jointed basalt is 5 degrees lower than the mean of all others, and the standard deviation is larger (table 1). This results, in part at least, from the relatively higher sphericity of talus blocks derived from jointed basalts and the very wide range of fragment sizes compared to fragments derived from sedimentary materials.

With this exception, the data indicate that rock type has little influence on form of escarpments, though rate of retreat may be directly connected with rock type.

POSITION OF BOUNDARY BETWEEN CLIFF AND SLOPE

A puzzling feature of many escarpments is the variation in position of the boundary between cliff and slope. Frequently the boundary is at the contact of the cliff- and slope-forming formations, rarely above this contact, and often below it, forming a vertical cliff in what is elsewhere a slope-making formation (figs. 2-a and b, 3, pl. 1). This variability is the key to understanding the mechanism of scarp retreat.

MECHANISM OF SCARP RETREAT

In many textbooks the formation of a talus at the base of a cliff in arid or semi-arid regions is described as the result of continuous shedding of fragments from the associated cliff. By implication, scarp retreat is then

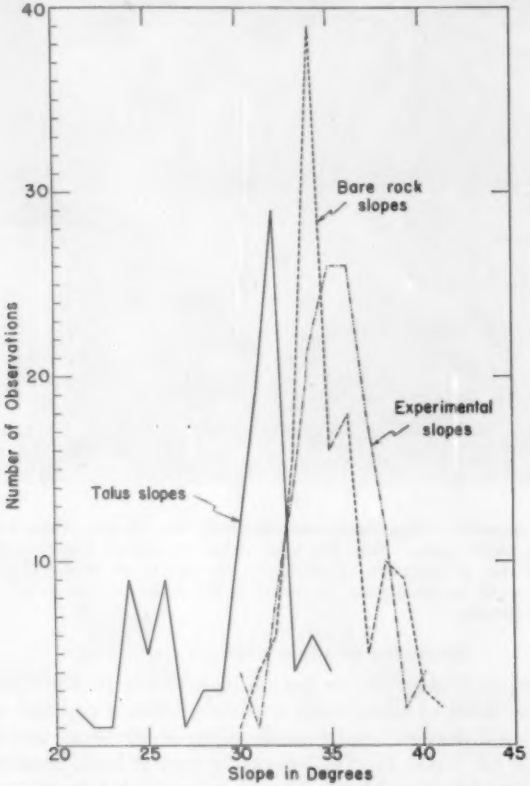

Fig. 4. Distribution of angles measured on talus slopes, bare rock slopes, and experimental apparatus. The secondary concentration of talus angles near 25° reflects the influence of columnar jointed basalt (see text and fig. 1).

visualized as the result of this continuous shedding of material along the whole cliff face. If this were the mechanism of retreat, however, there is no reason why the boundary between cliff and slope should vary in position, unless it reflected variations in the character of the slope- and cliff-making beds.

Detailed examination of cliff faces where variations in boundary between cliff and slope occur disclosed no related variations in rock character. A significant relationship was found to exist between the presence of sliderock on the slope and the state of weathering of the cliff face. Large sliderock accumulations were always associated with obviously fresh unweathered cliff faces, indicating recent large rock falls. Bare rock slopes and extensions of the cliff into slope-making formations were always associated with old, weathered cliff faces. While occasional individual fragments are undoubtedly shed from the cliff, the relationship indicates that large sliderock accumulations result almost wholly from single falls of large volumes of material, and that the shedding of individual weathered blocks is not a significant part of scarp retreat. It follows, then, that retreat must consist of a process which permits periodic large falls of rock from the cliff face, and preserves the characteristic cliff and slope angles through long periods of time. These conditions can be met by assuming the development of a fracture surface in the slope-forming material, at some angle near 45°, extending upward to the cliff-forming beds. This fracture should develop when the cliff extends such a distance into the relatively weak slope-forming beds that the strength of the material is exceeded by the weight of the overlying load. Slipping will then occur, with fracture of the cliff-forming beds along joints.

Obviously, a fracture surface of this type would be difficult to recognize in the field, since sliding would occur very soon after the fracture first developed. However, one such fracture surface, dipping 48° toward the cliff face and with displacement of approximately ½ inch, was observed in a small cliff in the Moenkopi formation near Lees Ferry, Arizona.

The process of retreat may be summarized as follows:

1. Formation of an escarpment by faulting or canyon-cutting, and development of a talus at the base of the cliff at an angle of approximately 32° (fig. 5-a).

2. Removal of the talus by weathering and erosion, developing a bare rock slope at an angle of 34-38° (fig. 5-b).

3. Erosion of bare rock slopes, partly by rill and sheet wash, partly by direct abrasion by sliderock, increasing the proportion of cliff to slope (fig. 5-c).

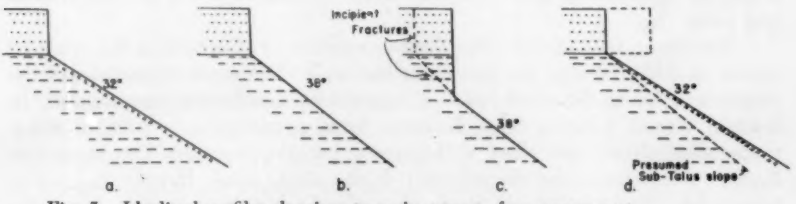

Fig. 5. Idealized profiles showing stages in retreat of an escarpment.

4. Yielding of the slope-making formation along a fracture surface at 40 to 50°, and collapse of cliff-making beds along joint planes, forming a talus over the rock slope at approximately 32° (fig. 5-d).

Further retreat is negligible until this talus is destroyed, when the cycle will be repeated. Rapid retreat of the scarp ceases when bare rock slopes at an angle equal to or greater than the angle of sliding friction can no longer be maintained. During the period of active retreat, successive cliffs and slopes would be approximately parallel to the originals, as indicated by Bakker and Le Heux (1947, p. 963-965). Once this phase of scarp retreat is passed, the conditions which produce parallel retreat are no longer present, and further reduction of the escarpment is accomplished by lowering of slope angles.

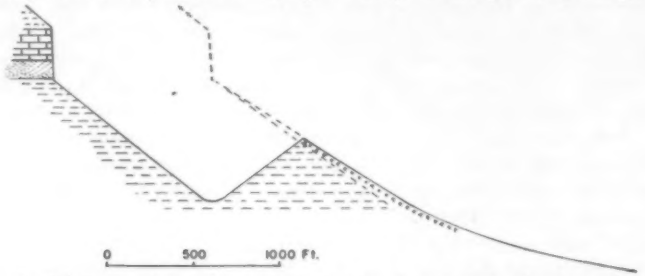

Fig. 6. Diagrammatic section of talus flatiron characteristic of western Grand Canyon. The talus flatiron is roughly triangular in plan.

The process outlined above would produce results which correspond to observed conditions. The preservation of the characteristic angles of cliff and slope, the relatively thin cover of sliderock over smooth rock slopes, and the correlation between large talus accumulations and fresh cliff faces are all explained. Variation in position of boundary between cliff and slope is a necessary consequence of this process. The similarity of scarp forms in different materials is explained as the result of the uniformity of talus angles and angles of sliding friction in different materials. Departures from the average result from special conditions, as in the case of the basalt cliffs mentioned above.

TALUS FLATIRONS

"Talus Flatirons" are minor slope forms having the general appearance of flatirons produced by inclined beds of resistant rocks, but are developed in rocks of relatively low resistance with horizontal or nearly horizontal attitude. They develop only where the cliff-forming beds are especially resistant to weathering, and where the slope-forming beds are relatively thick and weak (fig. 6).

The outer face of the talus flatiron consists of sliderock at the angle of repose characteristic of the particular materials. The inner slope, toward the escarpment, is undisturbed bedrock exposed by weathering and erosion. In western Grand Canyon talus flatirons form a conspicuous part of scarp topography. Here, the chief cliff-formers are the resistant Toroweap and Kaibab formations; the slope-former is the thick, weak Hermit shale. The talus, from 3 to 15 feet thick, forms an inclined resistant protective cover over

the weak Hermit shale, and as a result produces forms similar to the true flatiron resulting from differential weathering and erosion of steeply tilted sediments of varying resistance.

The form and history of talus flatirons confirms the conclusion that the sliderock-covered slope is relatively stable and that retreat of the scarp occurs only when the talus cover has been removed and the bare rock slope exposed. Otherwise, such remnants of the slope would not now be isolated from the rest of the escarpment.

TABLE 1
Talus Angles

Type of material	Number of observations	Mean, to nearest .1 degree	Standard deviation, to nearest .1 degree
1. Basaltic lava with columnar jointing; talus blocks variable, from 2″ to 8′	35	27.2	3.1
2. Blocky sandstone, with closely spaced joints; talus blocks 2″ to 24″	32	32.1	2.2
3. Massive cross-bedded sandstone; blocks equidimensional, 2″ to 6′	18	32.4	2.3
4. Massive sandstone, joints 6′ to 20′; cross-bedded, few talus blocks	14	32.2	1.2
5. Limestone; talus blocks blocky to platy, 1″ to 36″	6	32.1	1.2

TABLE 2
Rock Slope Angles

Type of material	Number of observations	Mean to nearest .1 degree	Standard deviation to nearest .1 degree
1. Thin-bedded silty sandstone	43	34.2	2.3
2. Thin-bedded friable siltstone and shale	10	36.1	2.1
3. Thin-bedded clays and bentonites	21	34.9	3.3
4. Thin-bedded siltstone and sandstone	21	35.1	1.3
5. Thin-bedded variable siltstone and sandstone	34	36.3	2.8

SUMMARY

Talus slopes and bare rock slopes fall generally within a very small range of angles in a wide variety of rock types. Scarp retreat in the regions studied is a discontinuous process consisting of sudden rock falls separated by long periods of relative stability. Active retreat occurs only when the sliderock accumulations can be removed and bare rock slopes established at approximately the angle of sliding friction for the materials involved. During this phase of development retreat is essentially by formation of successive parallel cliffs and slopes.

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ESSAY REVIEW

Norges Geologi; by OLAF HOLTEDAHL. Norwegian Geological Survey Publication 164. Bind I [Foreword, pre-Quaternary], p. xi, 583; 261 figs. Bind II [Quaternary, indices], p. 532; 224 figs; 2 general maps of Norway [bedrock, Quaternary]; 22 pls. in separate envelope. Oslo, 1953 (Norges Geologiske Undersøkelse, KR. 70.-).—Holtedahl's *Geology of Norway* is an impressive two volume work of 1100 pages, accompanied by 22 black-and-white plates in a separate envelope and by two large colored maps. One of the maps (compiled with the assistance of Johannes Dons) shows bedrock geology, and the other (compiled with the assistance of B. G. Andersen) shows glacial features. The text is profusely illustrated with maps, sketches, and photographs, many of the latter taken by the author. Literature references follow each major section, and a supplementary list at the end of Volume II includes titles through 1953.

The work had its origin in a course that Professor Holtedahl has given at the University of Oslo for more than thirty years. Some of the material was previously published in a shorter and more popular book, *Hvordan Landet Vårt Ble Til* (How Our Land Was Formed), which appeared in 1931. In preparing the present volumes Holtedahl has had the active cooperation of many Norwegian geologists and has been able to draw on much material in unpublished maps and manuscripts. The discussion includes all pertinent papers up to about 1949, and more recent work is mentioned in some sections.

Professor Holtedahl is writing primarily for Norwegians, and can scarcely be criticized for using the language his audience knows best. Yet one may properly voice a regret that the same material is not accessible in a better-known language. For this is a monumental work, deserving of worldwide study and recognition. A century and a half of geologic exploration of a large and complex area is here condensed, ordered, and clarified by a man who himself has been a major contributor to the basic data. Not content with the grand sweep of Norwegian geology alone, Holtedahl shows how the rocks and structures of his country fit into the larger pattern of northern Europe and the North Atlantic. For readers interested in the historical development of the science, the author takes pains to show how the major ideas in Norwegian geology originated, how controversies have sprung up, and how present-day opinions have been reached. Much of the material in the book is nowhere else available in easily accessible form, and it seems a major tragedy that so significant a contribution to world geology cannot have a wider circle of readers.

After a brief historical summary, Holtedahl places Norway in its regional setting at the western edge of the Fennoscandian shield. The shield is bounded to the east by overlying unfolded Paleozoic beds and on the south is faulted against Cretaceous and Tertiary rocks; its western margin is covered by Lower Paleozoic rocks folded during the Caledonian orogeny, and it is these rocks which underlie the greater part of Norway's rugged topography. An important detail of the regional geology is the graben in which Oslo is situated, a graben that has become famous both as a museum of rare alkalic igneous rocks and as a marvelously preserved segment of the outermost part of the Caledonian orogenic zone. The Caledonian folds and faults relate Nor-

way closely to Scotland and to Spitsbergen, and remarkable similarities of rocks and structures provide a link also to eastern Greenland and northeastern North America. As an explanation for these regional resemblances Holtedahl is more than a little sympathetic to Wegener's hypothesis, but he does not urge it strongly.

The Precambrian basement complex has received much less study in Norway than in Sweden and Finland. Few exact age determinations have been attempted, and relations of structure and degree of metamorphism have led to widely divergent interpretations. Two of the largest Precambrian areas flank the Oslo graben on the east and west. To the east are chiefly monotonous gneisses, continuous with the "gothic" gneisses of southwestern Sweden, dated by lead-uranium ratios as fairly late Precambrian (825-850 x 10^6 years); northward these are replaced by granite overlain by relatively unmetamorphosed ("jotnian") sediments. Immediately west of the Oslo area and south along the Skagerrak is a strip composed chiefly of paragneisses, the Kongsberg-Bamble formation; this is separated by a continuous zone of brecciation from the Telemark granite to the west; and the granite in turn is succeeded by the Telemark formation, dominantly quartzite and metamorphosed felsic volcanic breccia, which makes up the greater part of Norway's southernmost bulge. The relation between the Telemark and Kongsberg-Bamble formations has occasioned much argument; Holtedahl inclines to the opinion that both they and the eastern gneisses are not far separated in time, while others link the Kongsberg-Bamble rocks with older Precambrian structures in central Sweden ("svionian" or "svekofennidian"). With these Precambrian rocks in the south are associated some of the famous Norwegian pegmatites (Kragerø Risør, Arendal, Seterdal) which are extensively worked for feldspar and some of the rarer metals, and also the large molybdenite deposits at Knaben. Farther north the basement complex appears in several small areas, and then in the northernmost province forms another large expanse in which is located Norway's largest iron mine, a taconite deposit just south of Kirkenes. On older maps a broad area of Precambrian is shown along the coast southwest of Trondhjem, but recent work has demonstrated that much of this is highly metamorphosed lower Paleozoic rock.

Just north of the Oslo region and again in the far north the basement complex is overlain unconformably by sedimentary rocks, dominantly clastic, called the "sparagmite" series. These grade upward, with little or no break, into the lowermost Cambrian; since they are so different in character from other Precambrian rocks, and structurally so similar to the Paleozoic, they are commonly assigned by Scandinavian geologists to a separate time-unit, the "Eocambrian," corresponding most nearly to the Algonkian of North America. The sparagmite series has long been a favorite subject for controversy in Scandinavia, and Holtedahl himself has taken an active part in the debate. One of the questions concerns the origin of conglomerate layers which resemble tillites; in northern Norway old glaciated surfaces and associated varved clay make the identification certain, but in southern Norway the evidence is less convincing. Another problem is the environment of deposition of the bulk of the series; discontinuous red arkosic sandstones and abundant

conglomerate suggest in part a continental origin, but widespread limestones may indicate at least temporary marine incursions. The westward extent of the formation provides a further point of argument, for metamorphism accompanying the Caledonian orogeny blurs the distinction between sparagmite and lower Paleozoic. Holtedahl sees in the thickening of the sparagmite to west and north an indication that the Caledonian geosyncline had commenced to form as a series of basins before the end of the Precambrian.

From Cambrian through Silurian the geologic record is well exposed in Norway and has been studied in great detail. The best-known area is the Oslo graben at the extreme edge of the Caledonian deformation, where the rocks are neither greatly deformed nor metamorphosed. North along the east border to Trondhjem, and then again in the far north, are other large areas of well-preserved Lower Paleozoic rocks. Toward the west increasing deformation and metamorphism obliterate fossils and make the rock sequence difficult to unravel, except in a few isolated basins of only moderate folding along the coast.

At Oslo the oldest beds are middle Cambrian, the lower Cambrian appearing only some tens of kilometers to the north. The middle and upper Cambrian is chiefly black shale, a westward extension of the famous "alum shale" of Sweden, but here less rich in organic material and incapable of giving hydrocarbons on heating. Black shale continues into the lower Ordovician, becoming graptolitic, and then in the upper Ordovician gives way to alternating beds of shale and limestone. The Silurian of the Oslo area is mostly limestone, but the uppermost beds are brackish-water shales which change just north of Oslo to thick continental red beds (Downtonian). The Cambrian is subdivided chiefly on the basis of trilobites; in the Ordovician, *Dictyonema flabelliforma* is taken as the characteristic fossil of the lower part and the remainder of the period is subdivided by means of trilobites, particularly *Chasmops, Tretaspis,* and *Isotelus;* divisions of the Silurian have the characteristic brachiopods *Stricklandia, Pentamerus, Spirifer plicatellus,* and *Spirifer elevatus;* the brackish-water and fresh-water beds of the uppermost Silurian are locally famous for eurypterid and ostracoderm remains.

Lower Paleozoic beds in parts of the central mountain area and along the west coast can be correlated roughly with zones of the Oslo region, but correlation becomes more difficult to the north. In general limestone increases in relative amount and in thickness of beds, and volcanic material becomes prominent. Volcanic products are especially abundant in the Ordovician of the west coast; spilites, often showing pillow structures, are particularly common. To account for the volcanic rocks Holtedahl pictures an island arc off the west coast, discharging lava and pyroclastics into the sea. North of Trondhjem Silurian rocks are not known, but Cambrian and Ordovician continue far to the north. The last outcrop of Silurian to the north, on the island of Hitra west of Trondhjem, consists of uppermost Silurian beds (Downtonian) which are *later* than the major part of the Caledonian orogeny; this is a curious relationship, because the same beds north of Oslo are affected by the Caledonian deformation quite as much as are the strata beneath them.

To describe the Caledonian orogeny, Holtedahl begins with a typical

section through the zone of disturbance, from Oslo northwest to the coast. Just south of the capital lower Paleozoic beds are undisturbed; in the city they are moderately folded, and the folding increases northward; toward the mountains folding becomes isoclinal, large thrusts with imbricate structure develop, and metamorphism increases in intensity. Near the coast highly metamorphosed and granitized Paleozoic rocks become intricately mixed with metamorphosed sparagmite, basement complex, and Caledonian intrusives in structures which are only partly deciphered. Axes of folds and thrust plates have dominant westerly and northwesterly dips through most of the Caledonian zone, but near the coast eastward dips are conspicuous.

After this bird's-eye view of the deformation as a whole, Holtedahl gives detailed descriptions of the better-known areas involving Caledonian folds and thrusts. In the high mountains of south-central Norway is a huge overthrust block of dominantly eruptive rock resting on Lower Paleozoic sediments; in places two superimposed thrusts can be distinguished. At the east edge of the block is a conspicuous arkose-conglomerate which, like the Alpine molasse, was deposited during the thrusting movement and was partly overridden by the thrust block. West of the thrust lower Paleozoic beds reappear, metamorphosed and interlayered with intrusive material, for the most part in peculiar arc-like patterns representing steeply dipping synclines opening westward. The largest and best-known of these synclinal structures is the "Bergen arcs," two arcs of Paleozoic rocks concentric around the city of Bergen, separated by layers of anorthosite, norite, and related intrusives. Northeastward from Bergen, between it and the undisputed Paleozoic terrain near Trondhjem, stretches an area of rugged topography and extremely complex geology which is a current subject of dispute. It was described by Brøgger forty years ago as basement complex, but detailed work has shown more and more of it to resemble metamorphosed Paleozoic and sparagmitic rocks elsewhere. The presence of eclogite in several places is taken to indicate deep burial. Holtedahl and Dons map the area noncommittally as "mainly gneissic rocks of various origins, with structures wholly or in part Caledonian." North of Trondhjem is another area where gneisses and intrusives of uncertain age alternate with much-deformed Paleozoic sediments; especially notable here is a prominent thrust, roughly following the Swedish border, along which are developed the famous mylonitic rocks called "hårdskifer" or "Hartschiefer."

Intrusive rocks associated with the Caledonian orogeny belong chiefly to three well-defined types: gabbros and ultramafics related to the Ordovician extrusive rocks; hypersthene rocks, including anorthosite, norite, hypersthene syenite, and hypersthene granite; and trondhjemite and related low-potassium rocks. Normal granite and granodiorite are also common, but their age is often in doubt. Regarding practically all the supposed intrusive rocks there has arisen at least locally the question of a possible ultrametamorphic origin, and certainly the evidence for extensive migmatization and granitization is in some areas very strong. Some of Norway's richest mineral deposits are associated with Caledonian intrusives, especially the mafics and ultramafics; the largest and best-known are the sulfide deposits at Rǿros and Sulitjelma.

The Devonian of Norway, like the Devonian elsewhere around the northeastern Atlantic, consists of clastic continental deposits with many local unconformities. Exposures are limited to a few small areas along the west coast, probably remnants of a once more continuous layer, and two tiny areas near the Swedish border southeast of Trondhjem. The coastal rocks are folded and cut by low-angle thrusts, representing a disturbance which Holtedahl likens to the Acadian orogeny in North America.

The world-famous igneous rocks of the Oslo area, long thought to be Devonian, were established as Permian in 1931, when Holtedahl described lower Permian plant fossils and fresh-water fish from sediments below and interbedded with the lavas. The igneous rocks were named and described by Brøgger in a long series of papers (1894-1933) and are now the subject of a current series by several Norwegian petrologists. The rocks are well exposed, exceedingly variable, and to a large degree unique in composition and texture, so that they provide an almost inexhaustible field for petrologic study. Chemically most of the rocks have an abnormally high sodium content; texturally many of the lavas and dikes are characterized by abundant rhomb-shaped feldspar phenocrysts. Except for a few dikes in the Precambrian to the east and west the igneous rocks are limited to the Oslo graben, and the sinking of the graben is commonly explained by the removal of so much igneous material from below.

Brøgger's very numerous rock types can be grouped as (1) mafic rocks, represented by the plutonic "Oslo essexite" or kauaiite, hypabyssal camptonite, and extrusive soda-basalt; (2) syenitic rocks, whose best-known coarse-grained representative is larvikite and whose finer-grained varieties are the famous rhomb-porphyry dikes and lavas which excite the wonder of every geologically minded visitor to Norway's capital; (3) quartz-syenites and soda-granites, best-known in the plutonic nordmarkite which is prominent in the hills above Oslo, but represented also by a host of syenite and quartz-porphyry dikes. A prominent structural feature in the igneous part of the Oslo area is the "cauldron subsidence," a roughly circular down-dropped area bordered by a ring dike; several such structures have been discovered since the first one was recognized forty years ago.

Almost as famous as the igneous rocks are the contact-metamorphic rocks of the Oslo region, brought to the world's attention by Goldschmidt's monograph of 1911. These are formed where the lower Paleozoic limy shales are intruded by one or another of the intrusive rocks; the metamorphic aureoles are commonly 1 or 2 kilometers wide, and are magnificently uncomplicated by pneumatolytic effects. Some volatile material accompanied the Oslo eruptives, however, as is shown by several small mineral deposits in the Oslo area and by the large silver mines at Kongsberg a few kilometers beyond its western border.

The entire Mesozoic record of Norway is in an area measuring 8 x 2 kilometers on Andøya, an island north of the Lofoten chain. The sequence here consists of coal beds with middle Jurassic plants overlain by marine strata containing pelecypods and ammonites (and a recently discovered ichthyosaur) of late Jurassic and early Cretaceous age. Meager as the record

is, it serves to relate Norway to the very similar Mesozoic of eastern Greenland.

Tertiary rocks, so far as is known, are completely absent. During the late Tertiary Scandinavia was raised and tilted eastward, probably along faults whose presence is shown by prominent north-south valleys in western Norway and by submarine troughs just off the coast.

To this point Holtedahl brings his long story at the end of Volume I. The second volume, devoted to Quaternary geology and recent landscape development, is less easy for a foreign reader to follow because it demands an extensive knowledge of Norwegian place names. The intricate history of glacial advance and retreat and accompanying oscillations of sea level is nevertheless a most fascinating one.

The visible record is almost entirely of the last glaciation, since the latest ice advance removed or covered most deposits of earlier glaciations. Detailed soundings on the continental shelf suggest the presence during at least one older glaciation of an ice-tongue in the Skagerrak, which can be held accountable for the existence at several points along the west coast of typical boulders from far to the south and east—igneous rocks from the Oslo region, flint from Denmark, coal from Bornholm, porphyry from southern Sweden. Occasional deposits of sediment beneath the oldest moraines on the west coast contain fossils indicating a climate like the present, hence probably date from the last interglacial period. Mammoth teeth and musk ox bones from the interior are also commonly interpreted as remnants of an interglacial period but may possibly represent a climatic maximum after the last glaciation.

During the last glacial advance ice blanketed all of eastern and southeastern Norway; how completely the more rugged northern and western parts were covered is still a matter of dispute. Holtedahl uses DeGeer's time classification, separating the late-glacial and postglacial periods at a time about 6800 B. C., and dividing late-glacial time according to stages of the ice retreat. During the retreat Scandinavia stood lower with respect to sea level than today, so that complex glacial and marine deposits are found high above the present shoreline. Old strand lines at various levels are explained in part by discontinuous rise of the land and in part by eustatic changes of sea level; the most conspicuous of the old shorelines is the "Tapes level," corresponding to the "Littorina level" of the Baltic area. The fact that individual shorelines become higher inland has long been interpreted as an effect of rebound from the greater weight of ice in the interior. Late-glacial marine deposits are most widespread in the Oslo area; prominent features here are ridges consisting in part of morainal material, in part of marine deposits, evidently formed by the interaction of sea and ice. Holtedahl gives abundant detail about the interplay of glacial and marine erosion here and elsewhere in Norway, and likewise about the more orthodox glacial deposits found at higher elevations. The dating of late-glacial and postglacial events has been greatly helped by the development of pollen analysis, but varved clays have been less useful in Norway than elsewhere in Scandinavia.

The present Norwegian landscape is the result of stream and glacial erosion on a tilted fault block. On the gently sloping east side drainage is still

largely consequent, but faster erosion on the west has had time to become well adjusted to rock structure and hardness. Stream capture is prominent along the mountain divide, since streams on the steep west slope cut into the divide much faster than streams on the east. Extensive upland plateaus are conspicuous in the mountainous parts of Norway, and are customarily explained as old erosion surfaces; in southern Norway two such surfaces are commonly recognized, although some geologists have postulated many more. In recent years a question has been raised as to whether one or both of the principal surfaces may be primarily a result of glacial erosion or rock structure rather than peneplanation.

One perennially controversial subject among Norwegian geomorphologists is the origin of the fjords. It is not questioned that glacial erosion is responsible for present details of fjord topography, but there is room for argument on the relative importance of pre-glacial zones of weakness and glacial action itself in localizing the fjords. Holtedahl adopts an intermediate position, recognizing that some fjords follow zones of weakness and that some (especially the longer ones) are old stream valleys, but maintaining that short glaciers on the west coast may have carved their own fjords without benefit of favorable structure or pre-existing valleys.

A second geomorphological dispute concerns the "strand-flat," a topographic feature peculiar to the Norwegian coast, consisting of a lowland, up to several tens of kilometers wide, rugged on a small scale, lying in part above and in part below sea level. It may border highlands or it may form the entire surface of low islands and reefs; it may be cut by deep channels; in many places it is partly covered by loose material of both glacial and marine origin. The various possible roles of marine abrasion, subaerial erosion, glaciation, weathering and faulting in the development of such a surface have been debated for many years. Holtedahl himself thinks that many small coastal glaciers may be primarily responsible, and describes the similar work of such glaciers on the present coasts of Spitsbergen and Antarctica; erosion was aided by deep frost-weathering, and the surface may have been modified by later continuous ice cover and locally by marine erosion.

In addition to glaciation and geomorphology, Volume II includes brief discussions of such diverse subjects as human pre-history, groundwater, soil development, landslides, present-day glaciers, earthquakes, and meteorites.

Throughout both volumes, whether he is discussing ore deposits, fossils, structural relations, or geomorphology, Holtedahl shows an assured command of the essential geologic material and an ability to present fairly all sides of controversial issues. On most such issues he gives his own opinion and the reasons behind it, but his views are never obtrusive. He manages also to achieve a nice balance of subject matter, so that geologists of any stamp have no reason to feel that their specialty has been neglected. Perhaps glaciation has been somewhat overweighted, but an author can hardly be asked to conceal his own predilections completely. The work is a model of clear, judicious, balanced presentation of the geology of a forbiddingly complex area.

One can pick flaws, of course. A major omission is a comprehensive index; surely so complete and authoritative a work deserves something better

than the existing register of place names and list of references to economically important minerals. Then the locality names are often difficult or impossible to identify with names on the maps, but perhaps this is not so troublesome for the Norwegian readers to whom the book is addressed. Also it seems strange that Holtedahl should devote many pages to didactic discussion of elementary geologic principles—explanations of how glaciers erode, of the geosynclinal cycle, of the mechanics of thrust faulting. Perhaps he is trying to adapt the book to as wide an audience as possible, and perhaps scientifically well-informed general readers are sufficiently numerous in Norway to make it worthwhile; but in America those without geologic training would find technical parts of the book far too detailed and difficult, and geologists would regard the background explanations as out of place. But these are all minor criticisms of a most impressive piece of geologic writing.

For Professor Holtedahl the publication of these volumes marks a fitting climax to a distinguished career devoted to Norwegian geology. The Norwegian Geological Survey should take great pride in adding this ambitious work to its long series of excellent publications.

KONRAD B. KRAUSKOPF

REVIEWS

Experimental Nuclear Physics, Vols. 1 and 2; E. SEGRE, editor. Vol. 1, p. ix, 789; illustrated. Vol. 2, p. viii, 600; illustrated. New York, 1953 (John Wiley & Sons, vol. 1, $12.00; vol. 2, $15.00).—The vigorous expansion of nuclear physics since the war makes it extremely difficult for any individual to write a comprehensive treatise covering this flourishing field. The present series adopts the solution of the *Handbuch der Physik* in offering separate contributions by authorities in each of the major divisions.

The editor's hope has been to "bring the experimentalist up to date in experimental techniques . . . and indicate the broad lines of theoretical interpretation." The success of his efforts and those of his contributors is remarkable for so herculean a task; both volumes have the distinction of providing sufficient detail for the specialist and at the same time, at least in large sections, a clear exposition with a strong appeal for the general reader.

An extraordinary collection of material is contained in the Ashkin-Bethe article (Passage of radiations through matter, vol. 1), which seems destined to become a vade mecum of the high energy physicist. Extensive preparations of data and calculations on the proton range-energy relationship, the scattering of electrons, and the absorption of gamma rays in matter are presented, accompanied by critical judgments on validity and a physical discussion of major qualitative features.

Two sections are contributed by N. F. Ramsey (vol. 1). The first, on nuclear moments and statistics, surveys a field in which the author is a leading authority. It includes a thorough discussion of theoretical background and major experimental techniques, and has been published separately, with some additions from chemistry and the theory of solids, under the title of *Nuclear Moments* (Wiley).

The second article treats the nuclear two-body problem and related questions in nuclear structure. Although comparable developments of the theory already exist in texts of recent appearance (Sachs, Blatt and Weisskopf), the discussion of experimental material is more extensive than is to be found elsewhere in book form.

The chapter on detection methods by H. Staub (vol. 1) describes counters, associated electronics and cloud chambers. The discussion of scintillation and cerenkov counters is somewhat cursory; apparently this section was completed too early for inclusion of recent developments in these fields.

B. T. Feld's monograph of 390 pages (vol. 2) covers every aspect of the interactions of neutrons with matter. Primary topics include: n-n, n-p and n-e forces; neutron interactions with nuclei; neutron sources and detectors; diffusion in bulk matter; and coherent scattering phenomena. Especially noteworthy are the voluminous presentation of experimental data and the selection of very recent literature on theoretical interpretation from the periodicals.

"A survey of nuclear reactions" by Philip Morrisson (vol. 2) constitutes a relatively brief but remarkably lucid synthesis of the entire domain of nuclear physics. The material relating to classical nuclear physics is, again, to be found in texts, although generally without the pronounced emphasis on physical interpretation which distinguishes Dr. Morrisson's writing. The sections referring to high energy physics are culled from recent literature and not to be discovered in any text, to the reviewer's knowledge. The result is a very readable and coherent account, whose separate publication, with some expansion, would greatly benefit graduate students and others without a specialist's background.

ROBERT JASTROW

An Advanced Treatise on Physical Chemistry. Vol. IV, Physico-Chemical Optics; by J. R. PARTINGTON. P. xl, 688; illustrated. London and New York, 1953 (Longmans, Green and Co., Ltd., $15.50).—In commenting on the fourth volume of such a work as this, the reviewer finds it difficult to add to the generally favorable appraisal of previous reviews (this JOURNAL, v. 248, p. 444-446, 1950; v. 250, p. 389-390, 1952; v. 252, p. 761-762, 1953). This volume continues the thorough survey of the literature, old and new, which has characterized its predecessors, with many of the same general strengths and weaknesses in approach. In this review, therefore, the major stress will be laid on the subject matter, rather than on the success of the treatment.

Professor Partington includes under the heading physico-chemical optics the subjects of refraction and dispersion; polarization, diffraction, and light scattering; optical activity; the electromagnetic theory of light; magnetic rotation; piezo- and pyroelectricity; and the usual mathematical appendix covering an assortment of pertinent topics. Although the treatment applies to liquids and gases, as well as to solids, the material of this volume will be of particular importance to optical crystallographers, who will find in it discussions of most of the phenomena with which they are concerned. Although the volume contains full explanations and interpretations of most of the major

effects which matter exerts upon radiation, the absorption of light is discussed only summarily. This topic will be taken up more fully, along with molecular spectroscopy, in the next volume.

Professor Partington's historical interests have led him to devote what appears to this reader to be an inordinately large proportion of his treatment to obsolete theoretical approaches. The Maxwell theory of radiation is not introduced until the final third of the volume, while quantum mechanical interpretations are given an entirely subsidiary position. The postulate of a luminiferous ether was found to be unnecessary more than a generation ago, and few modern students are familiar enough with wave motion in elastic media for the ether model to be helpful in visualizing electromagnetic relations. The best excuse for including the Fresnel treatment in this volume is the assistance which it will give the modern reader who has occasion to study the classic 19th century researches.

In spite of this criticism, however, this volume remains a worthy companion to its predecessors, and the most complete and convenient source and summary of information on the parts of physical optics most likely to concern the chemist and the mineralogist. Aside from the important place which it deserves on library reference shelves, it will be a valuable acquisition for all scientists directly concerned with the optical properties of matter.

HENRY C. THACHER JR.

Contributions à la chronologie du pleistocène et des formes du relief en Belgique; by FRANS GULLENTOPS. Louvain Univ., Inst. géol., Mém., v. 18, 1954. P. 123-252; 24 figs.—This paper is a result of one of the many detailed studies of nonglaciated areas in western and central Europe recently in progress or completed, and combining to add significantly to knowledge of the stratigraphy of the upper Pleistocene. The chief interest in this contribution, which deals with southeastern Belgium, lies in the recognition of a threefold sequence within the Fourth Glacial stage. A lower loess with frozen-ground phenomena, and an upper loess with very restricted frozen-ground features are separated by a soil zone with evidence of thaw. The sequence suggests the lower Wisconsin and upper Wisconsin, separated by a mid-Wisconsin interval, visualized by many geologists in North America.

Local names are applied to the Belgian sequence, and, unfortunately in this reviewer's opinion, the Pleistocene sequence is presented under the Alpine rubric of Penck and Brückner. Good descriptions of the significant exposures are included.

RICHARD FOSTER FLINT

American Seashells; by R. TUCKER ABBOTT. P. xiv, 541; 100 figs., 40 pls. New York, 1954 (D. Van Nostrand Company, $12.50).—Malacologists, both professional and amateur, have been waiting many months for this book, originally planned for publication early in 1953. It is, however, a volume well worth waiting for. It is large in format, 7½ by 10, and contains 541 pages.

There are 24 full-page color plates; the shells superbly done on a black background giving them an almost three-dimensional appearance. In addition, there are 16 plates of black and white photographs, also on black backgrounds, which represent the very highest attainment in photography and halftone reproduction. Hundreds of line drawings throughout the text complete the illustrative part of the book.

Part I discusses the influence of mollusks in man's history, describes the groups that make up the Phylum Mollusca, and after a thorough discussion of the anatomy and shell variations within each group, adds a great deal of information regarding their food, enemies, reproduction—all the things that, taken collectively, make up their habits of life.

A chapter on collecting tells the novice where to find specimens and the best time to search for optimum results, going exhaustively into such subjects as dredging and trapping. Classification comes next, and the reader gets firsthand information from one of the Smithsonian's leading scientists on the proper way to label, arrange, and document his collection in a manner that will insure its having permanent value. Diagrams for shell cabinets are provided.

Part II describes more than 1500 American seashells, covering the Atlantic coast from Greenland to Florida, the West Indies, the Gulf coast to Central America, and the Pacific coast from Alaska to Baja California. The collector will have to learn many new names, as Dr. Abbott has brought the nomenclature completely up to date. This means that several well-known names must be ruled out, for reasons of priority or confusion with Mediterranean or Asiatic species. We find our old friend *Venus mercenaria* now listed as *Mercenaria mercenaria; Ostrea virginica* becomes *Crassostrea virginica;* the familiar southern mussel, *Volsella tulipa,* is now *Volsella americana*; and in Pacific waters the giant rock scallop long known as *Hinnites giganteus* becomes *Hinnites multirugosus.* This will be confusing, and perhaps aggravating to some amateurs, but it is done for the purpose of eventually stabilizing the nomenclature of malacology, and is a job long overdue. The author gives us a common or popular name for every species, be it rare or common. Each species is adequately described and its geographic range noted, and in many cases it is compared with others that might be mistaken for it. Keys are provided for several of the more difficult groups.

Dr. Abbott has done a splendid job in producing this book, and malacologists will be in his debt for many years to come, as it is certain to become the "Bible" of American shell collectors. This reviewer wishes that the figures on the plates had been numbered instead of lettered. They would be much easier to use.

There is an extensive bibliography, an index to subject matter and common names, and an index to scientific names.

P. A. MORRIS

The Coalfields of Great Britain; by SIR ARTHUR TRUMAN. P. xi, 396; 106 figs., 7 pls., London, 1954 (Edward Arnold, 63 *s* net) (New York, St. Martin's Press, $15.00).—According to the preface, this book is designed to supply the mining engineer and student of mining and geology "with a balanced account of the geology of the coal and of the structure and resources of the coal fields of Great Britain." It is further stated that the "features of the geology likely to arise in coal field work are fully treated." The reviewer is inclined to judge the work on the basis of these statements.

The introductory chapters (I - V) consist of a discussion of the various aspects of the general geology of Carboniferous rocks of Great Britain—lithology, stratigraphy, paleontology and paleobotany, and structure, but without the particular emphasis upon such aspects of coal geology and coal mining geology as seem to be called for. The petrology of the coal beds is given no consideration, and cyclical sedimentation, particularly its aspects as represented in the United States and its usefulness in stratigraphic and structural interpretations, is inadequately discussed. Faults are very important in the coal fields of Great Britain, but the specific character of the faults and the solution of specific fault problems are not considered. In discussing the origin of the coal fields, insufficient explanation is given of the break-up of originally large depositional areas into small isolated fields. More paleogeographic maps would have been useful in this discussion. Stratigraphic tables in the introductory chapters do not show the index or guide fossils at the various levels.

The considerable value of the book lies mainly in the eleven chapters prepared by well-informed collaborators. These chapters provide excellent and readable summaries of the geology of the different fields that will be of much value to the student of Carboniferous geology. They are well supplied with references. It is unfortunate that the maps accompanying several chapters are unsatisfactory, in that many places mentioned in the text are not shown on the maps. This is particularly true of the map accompanying the description of the coal fields of Scotland (chap. XVI.). A notable exception is the map in chapter XII (Leicestershire and Derbyshire). A general map showing the position of all the coal fields of Great Britain would have been very helpful to the foreign reader at least.

The book needs a summary chapter on coal resources, since undoubtedly this is a matter in which mining engineers are much interested, particularly concerning the quantity and position of coal resources in the areas extending out to sea and those underlying post-Carboniferous rocks.

The book is recommended to the attention of the general student of Carboniferous and particularly Coal Measure geology, but falls somewhat short of fulfilling the expectations with respect to coal geology and coal mining geology stimulated by the introductory statements.

GILBERT H. CADY

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